Phased Array Feeds & Primary Beams

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3rd October 2014
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

Physical reflector size

Feed

Dish

Uniform (Ideal)

Tapered (Realistic)
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: Phased Array Feeds!
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.
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 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

188 ports
RF

Frequency Conversion (optional)
188 ports
IF

Digitisation
188 ports
8-bit Nyquist

Polyphase Filterbank
188 ports
304 channels
9 beams
304 channels

Beamformer
9 beams

Polyphase Filterbank
16416 channels

Correlator

Other antennas
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 its 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:

\[ y_k[i] = w_k^T x[i] \]

  - 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:

\[ w_k = \hat{R}_n^{-1} \hat{\mathbf{v}}_k \]

  - 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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Obtaining a Steering Vector

- Can be done using single-dish ACM observations.

- Pointing the antenna at a strong source yields: $\hat{R}_{s+n}$

- The required steering vector is the Eigenvector of the difference corresponding to the dominant eigenvalue $\lambda$ (see Landon et al. 2010):

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

- 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

- 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

Channel 01, Frequency 0712 MHz, Pol 0
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

- Square
- Interlacing
- Diamond
- Spirograph
- Line
- Irregular
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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