Instrumentation for Radio Astronomy

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When thinking about engineering and the development of an instrument from a practical point of view the key concept to get across is that *any measurement is a loss in information.* In the case of astronomy, there is the potential to measure infinite frequency bandwidth, frequency resolution, time bandwidth, and time resolution across a 4π area of the sky. In reality, the instruments that we can build have limits on all these parameters, so we must be selective about which information we retain based on the scientific goals and engineering limitations.

1 Classic (dish-based) Interferometry

We start with dish-based interferometry, which I am calling 'classic' interferometry. This is a collection of antennas which have some sort of curved optics, are mechanically pointed, and correlated together to form visibilites. Examples of this type of array are the Very Large Array (VLA), Karoo Array Telescope (KAT-7), Atacama Large Millimeter Array (ALMA), and Westerbork Synthesis Radio Telescope (WSRT). Using this type of interferometric array, we will follow the path of electromanetic waves from the interface with the dish optics up to the final corrrelated visibilities.

- 'classic' interferometry using pointable dish optics, e.g. VLA and KAT-7/MeerKAT
- starting from the optics that focus the EM-waves, end up at the stored visibilities

1.1 Optics and EM Interactions

Given a dish diameter D, and an observing wavelength λ we think of two different interaction domains. When $D \gg \lambda$ light can be treated as a particle, this is the case for optical astronomy. When $D \sim \lambda$ then light needs to be treated as a wave, with complex interactions, this is the case for radio astronomy.

- directivity: we are choosing to prefer signal from one direction over another. coherent and incoherent structure leads to directivity, but the sky is always the same temperature
- EM scale for radio waves, bandwidth
- EM interactions lead to complex patterns and caustics, compared to optical where the scales are much different
- dish accuracy and efficiency

1.2 The Primary Beam

- basic primary beam of an ideal dish, airy disk from top-hat function
- sidelobes
- introduction of structure, practical primary beams like VLA

- how this effects sources: the vast majority of radio sources are stable on observing timescales, but we see variation as the source moves through the beam. beams are physical, depending on where you point, how much wind is blowing, ... lead to deformations

1.3 Antenna Feeds

- EM waves induce a current, which can then be recorded/digitized
- simple quarter-wave dipole is good for a monochromatic signal
- differtent types of antennas are used for different characteristics, there is no ideal: log-periodic, circular, dipoles, ...
- polarization
- impedence matching

1.4 Analogue Receiver Front-end

- or back-end, depending on whom you ask and in what context
- LNAs
- cryo-stats
- sky and system temperature
- amplifier/filter chains

1.5 Digitization

- ADC: the last analogue component
- bit resolution: wider bandwidth -¿ increase in power -¿ requires more bits in high RFI environment

1.6 Spectrometers

- the FFT
- signal conditioning with a FIR to create the PFB to reduce spectral leakage (RFI mainly)

1.7 Correlators

- correlation theory
- FX design
- XF design
- implementations: FPGA, GPU, CPU
- keep the cross-correlations, chuck the autos
- extras: delay and fringe-stopping
- bit quantization
- integration
- output visibilities

2 Aperture Arrays

- a generalization: a dish interfereometer without the dish
- PAPER, LOFAR
- sparse and dense aperture arrays
- generally used for low frequency
- PAFs are essentially AAs at the center of a dish feed

advantages:

- access to a larger subset of the sky
- can form multiple pointing directions
- science advantages to short baselines
- cheaper construction, don't need a large mechanical system to phycisally point

disadvantages:

- sources transit the elements, so the primary beam is more important to know
- many more electronic components for the same collecting area
- as the frequency scales up a dense aperture array becomes sparse

2.1 Beamforming

- forming a new primary beam out of multiple elements
- time-domain
- frequency-domain
- hierarchical
- incohrent beamforming for sky coverage

3 VLBI

- dish interferometer on very large scales -¿ high resolution
- technical issues: time distribution, station position, data transport and correlation

4 Single-Dish Astronomy

- measuring the auto-correlation
- relation to interferometry: sampling the large scale structure down to the sky DC
- technical issues: self-noise, RFI

5 The SKA

- what is purposed to be built: LFAA, MIDAA, MID-DISH, MID-SURVEY