A Modal and Quantum-Statistical Analysis of Imaging Phased Arrays and Interferometric Phased Arrays.

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A number of major projects are aimed at developing phased-arrays for radio astronomy; these include the Square Kilometer Array (SKA), the Low Frequency Array (LOFAR), the Electronic Multibeam Radio Astronomy Concept (EMBRACE), and the Karoo Array Telescope (KAT). All of these projects relate to microwave astronomy, but as technological understanding improves, phased arrays will also be constructed for submillimetre-wave and far-infrared astronomy. Two types of phased array are of interest: (i) Imaging phased arrays, where an array of coherent receivers is connected to a beam-forming network such that synthesised beams can be created and swept across the sky; the receivers may look at the sky directly or may be mounted on the back of a large reflecting antenna. (ii) Interferometric phased arrays, where the individual antennas of an aperture synthesis interferometer are equipped with phased arrays such that fringes are formed within the synthesised beams. In this way it is possible to extend the field of view, to observe completely different regions of the sky simultaneously, to steer the field of view electronically, and to observe spatial frequencies that are not available to the interferometer because the baselines cannot be made smaller than the diameters of the individual antennas. Of course, telescopes may operate in the `imaging' and `interferometric' modes simultaneously by configuring the arrays on the individual antennas to give low-resolution images, and cross correlating the outputs of the arrays on different antennas to give high-resolution data in the Fourier domain.

In this paper we describe the operation of imaging and interferometric phased arrays from a modal perspective, explaining how the behaviour of a phased array can be described completely in terms of the synthesised reception patterns, without any knowledge of the internal construction of the beam-forming networks. Beam patterns may be taken from electromagnetic simulations or experimental data. Crucially, we consider the general case where the synthesised beams do not have to be orthogonal or even linearly dependent; the close association with the mathematical theory of Frames is also mentioned. In the case of interferometric phased arrays, the arrays on the individual antennas do not even have to be the same. The ability to assess the behaviour of a system simply from the synthesised beam patterns separates the process of choosing the best beams for a given application from the process of understanding how to realise the beams in practice. It also suggests important techniques for analysing experimental data, particularly when cross talk between the primary feeds is present.

The paper explains how the powers, the fluctuations in the powers, and the correlations between the fluctuations in the powers at the outputs of different ports of a phased array can be determined from knowledge of the spatial state of coherence of the illuminating field, which for astronomical sources is usually fully incoherent: although not in the case of celestial masers. It is explained, by analogy with the behaviour of multimode detectors, how the quantum statistical behaviour of the source and noise fields can be included, taking into account the fact that the photon statistics may neither be fully bunched nor fully Poisson. This fundamental piece of work has implications for the way in which imaging and interferometric phased arrays are designed, how their performance is calculated, how they are characterised experimentally, and how astronomical data is analysed.