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# Beamforming in Radio Astronomy: State of the Art and Future Challenges

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Beamforming, the linear combination of signals from an array of sensors, has been used for radio astronomy since the first detection of radio waves from space. This presentation will review the state of the art in beamforming across radio astronomy. It will explain contemporary hardware and algorithms, and how they have been combined to improve the performance and efficiency of radio telescopes.

At the birth of radio astronomy, analogue beamforming was applied statically to increase the directive gain of antenna arrays. Since then, beamforming applications have become dynamic, including the agile steering of antenna arrays and, most recently, the adaptive control of telescope performance during observations. The more advanced benefits of dynamic beamforming are currently being explored on a variety of real-time digital signal processing platforms that allow rapid and repeatable modification of beamformer weights during measurements.

Current applications are focused on large aperture arrays that can observe multiple, widely-spaced directions on the sky at once and re-point instantaneously, and on phased array feeds (PAFs) that increase the field of view of reflector antennas. PAFs, with digital beamformers, additionally enable the live adaptation of a reflector antenna's characteristics. Using this technology, some antenna performance trade-offs are no longer frozen at design time and become configuration options that astronomers can vary from project to project.

Special attention will be given to the signal processing and spatial filtering techniques that are now being applied on radio telescopes equipped with real-time digital beamformers. Many techniques have been demonstrated that can improve measurement fidelity and reject unwanted radio frequency interference at the time of measurement. Offline beamforming, performed in software on recorded voltages or correlations, will also be discussed. This lies at the heart of synthesis imaging and is used in the performance evaluation of active array antennas. Further, offline beamforming can be used to maintain the most spatial information and calibration flexibility in data from single-dish PAF observations.

The presentation will conclude with a discussion of the future. This will include expected developments in beamforming hardware, firmware and software, and a survey of emerging signal processing techniques that may benefit radio astronomy. Key discussion points will include the scope for moving beamforming and beam calibration operations into more flexible software on GPUs and CPUs, and what the radio astronomy community can do to better harness the opportunities created by more flexible beamforming platforms.