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Coverage Efficiency Optimization and Experimental Verification Based on Conjugate Matching Method

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Reflector antennas are the primary configuration for large radio telescopes, and the optimization of beam synthesis technology in phased array feeds (PAFs), as their core components, directly determines system performance. Under ideal electromagnetic propagation conditions, each array element receives only the target signal component, allowing directional beam synthesis through simple phase compensation. However, in practical scenarios, the coupling effects of multipath reflections, artificial interference, and background noise result in spatially heterogeneous characteristics in the array-received signals.

In this context, optimizing beam synthesis factors has become a critical challenge in PAF design. Current approaches to solving beam synthesis factors are categorized into mathematical and physical methods. Mathematical methods treat the problem as an optimization process to achieve ideal illumination distribution by iteratively adjusting the weighting coefficients of PAF elements. Physical methods primarily include conjugate matching, maximum directivity coefficient, and maximum signal-to-noise ratio techniques. While mathematical approaches require complex iterations and precise channel modeling, the conjugate matching method (CCM) inherently aligns with radio telescopes' requirements for main-lobe directivity and polarization purity by matching the conjugate of the focal plane field. However, its accuracy is limited by the difficulty in directly measuring or calculating the focal plane field.

This study proposes an improved CCM scheme based on the reciprocity theorem: By exciting individual PAF elements and measuring the complex field strength of the reflector's far-field pattern, the receiving-mode weighting coefficients are indirectly derived, circumventing direct focal field measurements. A 6×10 L-band circularly polarized PAF was designed and integrated with a 20-meter-aperture reflector antenna (focal-to-diameter ratio 0.45). Joint simulations and experimental measurements validate the proposed method.

The CCM, rooted in matched filtering theory, maximizes signal-to-noise ratio (SNR) by setting the PAF weighting coefficients as the conjugate of the focal plane's complex field strength. For practical reflector antennas, however, the focal field distribution cannot be directly measured. Leveraging the reciprocity theorem, these coefficients are instead inferred from the far-field pattern.

According to the reciprocity theorem, the response of a PAF element to an incident plane wave from a specific direction (after reflection) is equivalent to the far-field strength in that direction when the same element transmits a signal. Consequently, the receiving-mode weighting coefficient for each element can be determined by the complex amplitude of the reflector's far-field pattern in the target direction when the corresponding element is excited. This forms the core logic of CCM calibration for generating compensation coefficients and weighting values.

Experimental results demonstrate that the proposed method achieves scanning gain fluctuations below 1 dB within six beam-widths, enabling multi-beam coverage. The reflector antenna attains a directivity coefficient of 47.09 dB and a cross-polarization suppression ratio of 11.54 dB, consistent with theoretical predictions. These results confirm a balanced optimization between wide-angle coverage efficiency and polarization purity.

In conclusion, this work addresses the co-design challenge of PAF and reflector antennas by proposing and validating a CCM-based beam synthesis solution. Through the development of an L-band PAF integrated with a 20-meter reflector (focal-to-diameter ratio 0.45), joint simulations and measurements confirm that the method effectively limits scanning gain fluctuations to within 1 dB across six beam-widths, resolving energy loss issues in wide-angle multi-beam coverage. This technology provides an engineering-ready pathway for efficient beam shaping in large-aperture reflector antennas, particularly suited for next-generation radio telescopes requiring multi-target observation capabilities. Future work will focus on real-time reflector deformation compensation algorithms to enhance robustness in dynamic environments.