Simulation of RFI Cancellation Using Subspace Projection Algorithm for PAF Receiver (Postprint)

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Abstract

The simulation of radio frequency interference (RFI) cancellation by applying a spatial filtering technique for phased array feed (PAF) is presented. In order to better reflect the characteristics of PAF, a new signal model is to add the coupling coefficient among elements of PAF to the conventional array signal model. Then the subspace projection (SP) algorithm is used to cancel RFI from the correlation matrix of the signal, and finally, the 2D power image is drawn. The power variation of signal-of-interest direction and RFI direction before and after using the SP algorithm is analyzed. The new signal model and simulation strategy can be used to test and verify the beamformer.

Full Text

Preamble

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Simulation of RFI Cancellation Using Subspace Projection Algorithm for PAF Receiver

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Abstract

This paper presents a simulation of radio frequency interference (RFI) cancellation by applying spatial filtering techniques to phased array feed (PAF) receivers. To better reflect the characteristics of PAF, we propose a new signal model that incorporates coupling coefficients among PAF elements into the conventional array signal model. The subspace projection (SP) algorithm is then used to cancel RFI from the signal correlation matrix, and two-dimensional power images are generated. The power variation in both the signal-of-interest (SOI) direction and RFI direction is analyzed before and after applying the SP algorithm. This new signal model and simulation strategy can be used to test and verify beamformer performance.

Key words: methods: analytical -techniques: radar astronomy -telescopes

1. Introduction

The phased array feed (PAF) receiver, as a next-generation microwave receiving system, has been widely studied worldwide. However, applications of spatial interference cancellation using PAF remain rare in radio astronomy (Wang et al. 2021). Currently, most RFI mitigation methods target narrow-band, pulsed, or intermittent interfering signals based on time-frequency characteristics, where RFI is typically blanked. This paper presents a simulation of RFI mitigation based on spatial information using a PAF receiver. We establish a signal model with planar coupling effects and analyze its impact on the main beam. The subspace projection (SP) algorithm is employed to simulate RFI cancellation in a PAF receiver, and we study the output power performance in both SOI and RFI directions.

Unlike conventional arrays, PAF is a tightly distributed array designed for reflector antennas. The conventional array signal model cannot account for coupling effects among PAF elements. This paper examines the impact of PAF coupling effects on data correlation operations from baseband data, then simulates and analyzes radio telescope patterns and RFI cancellation by combining antenna simulation software with MaxSNR and SP algorithms.

The Mk II PAF receiver developed for ASKAP by the Commonwealth Scientific and Industrial Research Organization in Australia had its frequency range compressed from 0.8-1.74 GHz to 1.2-1.75 GHz due to interference from mobile phone and digital television signals after testing at Parkes and Effelsberg (Chippendale et al. 2016). The American FLAG project considered adaptive filtering technology to mitigate RFI in beamforming and verified the performance of Linear Constraint Minimum Variance (LCMV) and SP algorithms for PAF (Warnick et al. 2007; Landon et al. 2012). While no PAF receiver has yet been fully deployed in China, several research groups—including the Five-hundred-meter Aperture Spherical radio Telescope (FAST) team at the National Astronomical Observatories (Chai et al. 2020) and the Qi Tai Telescope (QTT) project (Wang 2014)—are actively pursuing research.

QTT, the world’ s largest fully steerable single-dish radio telescope currently under construction, was selected by *Nature* as one of the most noteworthy science projects of 2023. Its prime focus will be equipped with a 96-element dual-polarization PAF array (Ma et al. 2019), where beamforming will be implemented on GPUs in the digital terminal (Pei et al. 2022). This PAF receiver represents the most complex system in QTT and poses significant development challenges. However, a suitable numerical model can facilitate analysis, validation, and improvement of beamforming algorithms. Therefore, developing a baseband numerical model and algorithm simulation that accurately reflects PAF receiver characteristics is essential. Ivashina et al. (2011) optimized the joint field of view and beam rotational symmetry of a PAF receiver through numerical simulations for the Westerbork Synthesis Radio Telescope (WSRT) project.

The remainder of this paper is organized as follows. Section 2 presents the new PAF model, detailed definitions, and mathematical formulation of SP beamforming. Section 3 describes our customized simulation strategy and verifies the performance of the new signal model on the main beam for the QTT-PAF model. The SP algorithm is used to cancel RFI-containing data in the beamformer, and power variations before and after SP application are analyzed. Section 4 provides a summary.

2.1. Signal Model of PAF in Time

As depicted in Figure 2 [Figure 2: see original paper], assuming narrowband operation of an M-element PAF, the M × 1 complex baseband data vector at time sample n is given as:

where s[n] is the SOI with array response vector a (normalized spatial characteristics of celestial bodies in PAF, sometimes called array manifolds, including effects of the reflector dish and PAF geometry), and d[n] is a single interfering source with corresponding array response v (usually not in the main focus direction). In general, a is constant because telescopes are mechanically controlled to maintain the same line of sight as the SOI. As the interferer is random or the dish tracks the SOI, v changes with time. c is the M × M matrix describing PAF coupling characteristics, detailed in the following section. The noise vector n[n] is assumed to be spatially non-white Gaussian, with correlation arising mainly from PAF coupling effects. Signals s[n], d[n], and n[n] are assumed to be temporally wide-sense stationary. Beamformer output y is the weighted sum of signals received by each array element, computed as:

for i = 1, ···, M.

2.2. Signal Correlation Analysis

Typically, the signal sampling rate is much faster than interferer movement, so v is approximated as constant during a short-time integration (STI) window. The

SOI and RFI are assumed uncorrelated with each other and with the noise in each receiving chain. The covariance matrix of the signal in the jth STI window of length T samples is estimated as:

where X is the M × T matrix representing the voltage output of PAF over T sample points.

N is the M × M noise covariance matrix, assumed to be diagonal. We assume N = λ^2I, where λ^2 is noise power and I is the identity matrix.

Rs is the 1 × 1 SOI covariance matrix, representing SOI power in an STI window. The generated SOI has Gaussian, zero-mean, white, and stationary characteristics.

Rr is the Q × Q RFI covariance matrix, where Q is the number of interferers.

c is the M × M coupling coefficient matrix among elements. The tight arrangement of PAF elements increases radiation bandwidth and distorts the beam pattern. The coupling phenomenon means that when a wave arrives at the PAF, the induced current in one element radiates some energy back to other PAF elements, with stronger induction among nearby elements and weaker induction among distant ones. In the model shown in Figure 3 [Figure 3: see original paper], elements are placed in a rectangular coordinate system, and the distance between two elements can be expressed by a tuple (Δx, Δy). When correlating PAF signals, the coupling effect caused by element distribution can be represented as a covariance matrix C:

where σ is the coupling effect coefficient (generally determined by inherent element material characteristics). Thus, c is the Cholesky decomposition matrix of C.

2.3. The SP Algorithm

The mathematical principle of subspace projection in the PAF receiver can be summarized as a linear transformation from one vector space to another. Compared with waveguide feeds, the PAF receiver can extract spatial characteristics (position information) of target signals, enabling selective mitigation or acceptance of signals. This provides a new approach for RFI cancellation in single-aperture radio telescopes.

In an STI window, the expected signal value is estimated from the covariance matrix, and spatial information is extracted through array processing methods. Let S represent the output signal space of PAF. According to different radio astronomical signal processing objectives, S can be divided into three subspaces: SOI subspace, RFI subspace, and noise subspace. These subspaces are expressed as:

where R(•) represents column space. We want to project the PAF output signal into a special space W that is perpendicular to V and belongs to S. Using matrix orthogonal projection, the expression is:

such that P v = 0. Therefore, when the spatial filter is applied to the data covariance matrix, all interference energy will be nulled. The column space of P can be described as:

where the column space of I is the whole space W = ^M. This can be understood as finding a set of basis vectors that does not contain RFI spatial features, such that the projection of RFI-containing data onto this basis yields zero.

The P transform is then applied to the PAF weight w to obtain the weight vector ω with RFI mitigation capability:

In this linear transformation, P has an important property: the projection only takes effect in the first mapping and does not superimpose multiple mapping effects. This idempotency property determines that $P^2 = P$.

3. Simulation

Our simulation design is based on the QTT PAF model. As shown in Figure 4 [Figure 4: see original paper], a detailed numerical model is used for 32 of the 96 elements, following the design of Ma et al. (2021). In this numerical model, we generate the data described in Equation (1) to realize beamforming simulation and performance analysis of the SP algorithm for RFI cancellation.

3.1. Simulation Conditions

The tools used in this simulation are GRASP-E and Python. The former is a free student version of general-purpose reflector antenna design software from TICRA in Denmark,^{6} and the latter is an open-source data processing and plotting language. The entire simulation strategy consists of four parts, with the flow chart shown in Figure 5 [Figure 5: see original paper].

Main Reflector: GRASP-E simulates the pattern of the 110 m reflector. As specific design details are not disclosed, the influence of the support structure is not considered. Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper] show the reflector model and pattern.

Signal Generator: This generates the complex exponential PAF signal including SOI, RFI, and noise (Li et al. 2023), satisfying the statistical description in Equation (3). The main parameters are: (a) element position parameter table (which largely determines beam shape); (b) proportional coefficient between element spacing and operating frequency; (c) ratio of sampling rate to signal frequency; (d) spatial location information of SOI and RFI; and (e) SNR of SOI and RFI, where $10 \log_{10}(Ps/Pn)$ with Ps as signal power and Pn as noise power.

SP-Beamformer: This calculates vector P and implements beamforming. The weight expression is $\omega = P\,\omega\{maxSNR\}, \; where \; \omega\{$maxSNR$\}$ is the MaxSNR beamformer weight. This includes signal covariance calculation, matrix decomposition, and other operations. Key parameters are: (a) STI window size; and (b) normalized spatial characteristics of RFI. The error between measured estimated $\hat{v}$ and actual v plays a key role in RFI cancellation (v is given directly for convenience; this paper does not address v measurement and estimation).

Visualization of Power: Radio astronomy often focuses on measuring celestial radiation power. In a PAF STI, average power can be measured through digital beam control:

where ω is the normalized spatial direction vector. Power measurement in an STI is realized by applying this formula to traverse the imaging area.

3.2. Influence of Coupling Matrix in PAF Beamforming

To analyze the influence of coupling coefficients in PAF beamforming, 32 of the 96 QTT-PAF elements are selected to form a single beam. These elements, shown as selected in Figure 4 [Figure 4: see original paper], are located at the PAF center and exhibit good directional characteristics. The Signal Generator creates an observation signal with power far below noise level and without RFI, representing deep-space exploration in a non-interfering environment. Detailed parameters are shown in Table 1 .

The Signal Generator produces two data types: one with coupling coefficients and one without. As shown in Figure 8 [Figure 8: see original paper], correlation matrices for both data types are plotted, along with the coupling coefficient matrix.

Table 1: SOI Simulation Parameters

Parameters	Value
noise	white noise
SNR(in)/dB	-30.99
SNR(out)/dB	-29.86
f/GHz	1.5

Figure 9 [Figure 9: see original paper] shows the 2D telescope power images under the conditions in Table 1. Compared with images without coupling coefficients, those with coupling coefficients exhibit a deformed main lobe shape, lost rotational symmetry, and shallower first null depth. This aligns with our understanding of mutual coupling effects in PAF.

The correlation results in Figure 8 [Figure 8: see original paper] show that the coupling coefficient enhances inter-element correlation while retaining conventional array autocorrelation. We apply MaxSNR beamforming to the results in Figure 8. Under ideal matching conditions, the telescope pattern is obtained by weighting the Main Reflector and PAF patterns. The area around the main lobe is selected for 2D imaging using Visualization of Power, as shown in Figure 9 [Figure 9: see original paper].

3.3. Subspace Projection RFI Cancellation

Subspace projection controls the null position of a telescope pattern. In the presence of interference, the SP algorithm uses projection operator P to cancel RFI in the $M \times M$ correlation matrix R estimated within an STI.

Typically in radio astronomy, the telescope main lobe aligns with the target source while interference enters through sidelobes. Table 2 parameters simulate the PAF array signal with coupling effects when interference is present, assuming a single random interferer (excluding the SOI direction).

Table 2: SOI and RFI Simulation Parameters

Parameters	Value
noise	white noise
SNR(in)/dB	-30.99
SNR(out)/dB	-29.86
f/GHz	1.5

We apply both SP-Beamformer and MaxSNR beamformer to the element signals, then calculate the relationship between SNR and STI in both SOI and RFI directions. Results are shown in Figure 10 [Figure 10: see original paper]. We found that RFI presence affects power performance in the SOI direction, and this effect depends on STI size—contrary to our initial understanding.

In Figure 10(a), compared with pure SOI results, RFI presence causes energy elevation in the SOI direction, primarily due to energy leakage from the RFI direction. After SP-Beamformer processing, this energy elevation is improved, and the improvement stabilizes with increasing STI size. In Figure 10(b), RFI is canceled by nulling after SP-Beamformer processing. This cancellation achieves a large dynamic range that does not improve with STI size but meets RFI cancellation requirements. Overall, the SP algorithm effectively cancels RFI but cannot fully restore SOI power, due to $v \neq 0$.

In conclusion, appropriately increasing STI size stabilizes SP algorithm performance in restoring SOI, though complete restoration remains impossible. In strong RFI environments, STI size has less effect on cancellation because RFI dominates signal power. Therefore, beamformer design should consider both SOI power restoration stability and GPU performance when selecting STI size.

Figure 11 [Figure 11: see original paper] shows QTT sky power images from Visualization of Power. Figure 11(a) demonstrates that RFI from sidelobes becomes the main response area, covering the central SOI response. Figure 11(b) shows the image recovered by SP technology, where RFI is completely eliminated and SOI response is highlighted. Figure 11(c) shows the difference between the two images.

4. Conclusion

The main contributions of this paper are: (1) From a data correlation perspective, we establish an array data model reflecting planar PAF coupling characteristics, showing that coupling effects cause loss of rotational symmetry and shallower first nulls. (2) We complete simulation combining PAF and reflector antenna patterns, using the SP algorithm to cancel RFI in the PAF receiver and generate 2D power response images, calculating SOI power changes in RFI directions before and after SP application.

Although our model simulation focuses primarily on the digital backend without considering LNA, antenna efficiency, and other factors, the data model and simulation strategy can verify beamformer performance and shorten PAF receiver development time.

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