Analysis and Research on Key Technologies for Sparse Arrays in Radio Astronomy (30-300 MHz Band) - Postprint

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Abstract

The 30–300 MHz Very High Frequency (VHF) band represents a critical radio astronomy band, with observations in this frequency range employing antenna array configurations. Sparse arrays offer advantages of high spatial resolution, low sidelobe levels, and reduced cost. Furthermore, array synthesis weighting can effectively shape the main beam of the antenna array while suppressing both the Maximum Side Lobe level and Far Side Lobe level. This paper first reviews the development and current status of VHF sparse array research in radio astronomy, along with the challenges to be encountered. We propose first optimizing the arrangement of elements in the optimal sparse array, and further present a signal processing architecture for sparse VHF radio astronomy arrays that integrates high-performance computing platforms with FPGA SOPC. The weighting parameters for each array element frequency point are computed on a Graphics Processing Unit (GPU) or cloud computing platform, then transmitted via high-speed bus to front-end signal processing boards, where FPGA SOPC completes the distribution of these weighting parameters. Additionally, we analyze and calculate the data rates for multi-beam scenarios, enabling real-time parameter configuration. The results of this paper provide a technical foundation for the deployment of next-generation large-scale VHF antenna arrays.

Full Text

Abstract

The Very High Frequency (VHF) band (30–300 MHz) is a crucial observational window for radio astronomy, with important research value in space weather, solar radio bursts, planetary emissions, pulsars, transients, and cosmic reionization. Modern radio telescopes such as the VLA, GMRT, LOFAR, and SKA all target this band. Due to the long wavelengths, observations require phased array configurations. Sparse arrays offer advantages including high spatial resolution, low sidelobe levels, and reduced costs. Further array synthesis weighting can effectively shape the main beam and suppress maximum sidelobe levels.

This paper reviews the development and current status of sparse array research for radio astronomy in the VHF band, identifies key challenges, and proposes a technical architecture. The approach involves first optimizing the element layout of the sparse array, then implementing a signal processing framework that integrates high-performance computing platforms. Weighting parameters for each array element and frequency channel are computed on Graphics Processing Units (GPUs) or cloud computing platforms, then transmitted via high-speed bus to front-end signal processing boards for distribution through FPGA-based System-on-Programmable-Chip (SOPC) architectures. The data rates for multi-beam configurations are analyzed, enabling real-time parameter updates. These results provide a technical foundation for future large-scale VHF array deployments.

Keywords: VHF; optimization algorithm; sparse array; array synthesis; low sidelobe

1. Introduction

The VHF band (30–300 MHz) is essential for radio astronomy, enabling studies of space weather, solar radio bursts, planetary emissions, pulsars, transients, and cosmic reionization. Representative instruments include the Meterwave Radio Telescope, SKA, LOFAR, VLA, and GMRT. The long wavelengths in this band necessitate array configurations of multiple dipole antennas. Beamforming through weighting creates high-gain beams for sensitivity, while the complex radio environment demands high dynamic range to suppress interference.

The fundamental approach for high-resolution, high-sensitivity VHF observations involves stations of hundreds of antenna elements. Beamforming occurs at two levels: station-level (Station-Beam) and inter-station correlation. Station beams are formed from one-dimensional data streams representing fixed directions, while inter-station correlation creates two-dimensional sky snapshots. The first level provides tracking through weighted summation; the second enables coherent combination for high-resolution imaging.

2. Sparse Arrays and Their Advantages in Radio Astronomy

2.1 Dense vs. Sparse Array Comparison

Traditional regular lattice arrays face grating lobe problems during wide-field scanning. The minimum element spacing d often violates the grating lobe-free condition at upper frequencies, especially at large scan angles θ. The condition $d < \lambda/(1+\sin\theta_{\text{max}})$ becomes difficult to satisfy as θ increases. Sparse arrays with non-uniform element spacing break the periodic energy distribution, eliminating grating lobes while increasing aperture and resolution. They achieve low sidelobes without amplitude weighting and reduce costs.

Table 1 compares dense and sparse array parameters. For the same number of elements, sparse arrays provide higher gain and resolution. In the low-frequency band, sparse arrays demonstrate superior survey speed. Figure 3 illustrates this advantage.

2.2 Grating Lobe Suppression

For ultra-wideband arrays scanning ±45°, grating lobes appear at the upper frequency limit, causing catastrophic effects on observations. Sparse arrays, particularly ultra-wideband configurations, address this by optimizing the Maximum Sidelobe Level (MSLL) as the primary objective. After determining the sparse layout, element weighting further shapes the beam across multiple parameters including beamwidth and far sidelobe levels, achieving sidelobe suppression exceeding 30 dB.

2.3 LOFAR Sparse Array Implementation

LOFAR's LBA (10–80 MHz) uses random exponential distribution layouts to obtain sparse configurations. Designers integrated antenna pattern synthesis optimization with two main objectives: (1) minimizing peak sidelobe levels, and (2) increasing spatial-frequency sampling points. For the LWA-1 elliptical array configuration, the optimization minimized maximum sidelobes using the antenna array reception vector as the objective function. Starting from a standard hexagonal layout, iterative adjustments optimized element positions under constraints of station area and minimum element spacing, with a cost function to limit strong source impacts.

Figure 5 shows LOFAR's 96-element sparse configuration. Figure 6 compares regular and optimized LWA-1 layouts. Non-regular sparse arrays produce smoother sky scanning images but increase optimization search difficulty due to greater position freedom. However, they can achieve lower peak sidelobe and far sidelobe levels.

3. Challenges for Sparse Arrays in Radio Astronomy

Multiple factors determine VHF sparse array performance: element radiation patterns, array geometry, sky radiation distribution, interference sources, and errors (placement, amplitude, phase). Figure 8 illustrates these relationships.

Key challenges include:

3.1 Optimization Search Difficulty

Finding the global optimum for sparse arrays is NP-hard. Different constraints require different algorithms, and all optimization algorithms risk converging to local optima. Radio astronomy imposes unique constraints not fully studied in microwave applications. Systematic research on VHF array constraints remains limited.

3.2 Far Sidelobe Confusion Noise

Radio astronomical signals are weak; far sidelobes introduce confusion noise. Following reference [29], Far Sidelobe Confusion Noise (FSCN) is defined as:

$$\mathrm{FSCN} = \mathrm{PSF} \cdot I_s$$

where I_s is the brightness function of multiple interfering sources and PSF is the point spread function. CLEAN algorithms mitigate this by removing bright sources, but require precise knowledge of source positions and amplitudes. High sidelobe suppression (>30 dB below main lobe) is essential.

Simulations comparing Taylor and Dolph-Chebyshev weighting show the latter achieves 30 dB suppression, while Taylor methods fall short. Further investigation of various synthesis algorithms is needed.

3.3 Broadband Beam Pattern Complexity

For broadband, irregular sparse arrays, beam patterns vary with frequency, element count, and weighting scheme. Precise beam contours require simulation based on the specific sparse layout. Multi-band imaging demands knowledge of beam patterns across 3–4 frequency bands, requiring massive computational resources.

3.4 Error Modeling

Sparse arrays introduce significant position, phase, and amplitude errors. Existing studies often assume ideal conditions, but practical systems require comprehensive error modeling:

Amplitude Errors: Caused by gain response inconsistencies, modeled as multiplicative errors Γ_ρ independent of signal direction.

Phase Errors: Caused by phase response inconsistencies, modeled as additive errors Γ_ϕ.

Weighting Frequency Deviation: In ultra-wideband systems, weighting at the center frequency f_c with bandwidth BW causes deviation at band edges f_{high} and f_{low}. The degradation $\Delta\mathrm{MSLL}$ is a function of BW/f_c.

Element Position Errors: Installation tolerances cause position errors Δr_{mn}, affecting pattern calculations.

A comprehensive error model combining these factors is essential but computationally intensive.

4. Signal Processing Architecture

4.1 System Overview

A GPU+FPGA SOPC architecture is proposed (Figure 11). GPUs compute weighting parameters for all elements across frequency channels, transmitted via high-speed bus to front-end FPGA boards for distribution. This enables real-time configuration.

The hardware platform (Figure 12) uses: - GPU/cloud servers for computation - High-speed network communication - FPGA-based ADC control, channelization, and weighting - ZYNQ-7000 FPGA boards with 10 Gbps Ethernet capability

4.2 GPU Computing Pipeline

For each frequency channel, the array factor is computed as:

$$F_i(\theta,\phi)=\sum_{m=1}^{M}\sum_{n=1}^{N}w_{mn}\cdot f_{mn}(\theta,\phi)\cdot e^{jk_i[d_n(\sin\theta\cos\phi-\sin\theta_0\cos\phi_0)+d_m(\sin\theta\sin\phi-\sin\theta_0\sin\phi_0)]}$$

where $k_i = 2\pi/\lambda_i$, w_{mn} are weighting factors, and f_{mn} are element patterns.

GPU parallelization handles: - $N_{\text{elements}} \times N_{\text{polarizations}} \times N_{\text{channels}}$ threads - Synchronization to avoid weighting misalignment - Database coordination for element patterns, weighting parameters, sky models, and error parameters

For a 1024-element dual-polarization array with 1024 channels and 4-byte parameters, the data rate is:

$$\text{Data Rate} = 1024 \times 2 \times 1024 \times 4 \times 8 \approx 560 \text{ Mbps}$$

4.3 Feasibility Analysis

GPU Platform: NVIDIA Tesla V100 provides 7 TFLOPS single-precision performance, sufficient for array factor computations. Parameter updates need not be extremely frequent for wide beams.

FPGA Communication: ZYNQ-7000 FPGAs support 560 Mbps data rates with integrated 10 Gbps Ethernet, enabling real-time parameter distribution.

5. Conclusion

High-performance VHF radio astronomy requires coordinated technologies. This paper proposes a technical framework for experimental arrays, combining sparse layout optimization with GPU+FPGA signal processing. The approach will be validated through solar radio observations, providing a foundation for large-scale VHF array deployment.

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Note: Figure translations are in progress. See original paper for figures.