# Application of Polyphase Filter Bank Technology in Low-Frequency All-Sky Total Power Measurement Experiments: Postprint

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## Abstract

As one of the important methods for probing the cosmic reionization epoch, the core objective of low-frequency all-sky total-power experiments is to search for the extremely weak neutral hydrogen 21 cm signal from the cosmic reionization epoch in the all-sky total-power spectrum within the frequency range of 50–200 MHz. Currently, fast Fourier transform (FFT) is commonly used to compute power spectra. However, the spectral leakage problem inherent in FFT prevents complete removal of radio frequency interference (RFI), thereby severely hampering the extraction of the weak cosmic reionization signal. Polyphase filter bank (PFB) is a technique that divides signals uniformly in frequency and can replace FFT for power spectrum computation. This paper introduces the fundamental principles of PFB and its implementation based on Compute Unified Device Architecture (CUDA), compares the performance of PFB and FFT through simulations, and also examines performance differences among PFBs of various orders. The results demonstrate that PFB technology exhibits a flatter passband response, a narrower transition band, and superior out-of-band rejection. Finally, by processing observational data from the Tianma Telescope and data generated from low-frequency total-power experiments, the superiority of PFB technology is validated, providing an effective solution for spectral analysis in all-sky total-power experiments.

## Full Text

### Preamble

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# Application of Polyphase Filter Bank Technology in Low-Frequency All-Sky Total Power Measurement Experiments

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## Abstract

As one of the important methods for probing the cosmic reionization epoch, the core objective of low-frequency all-sky total power experiments is to detect the extremely weak neutral hydrogen 21 cm signal from the cosmic reionization period in the all-sky total power spectrum across the frequency range of 50–200 MHz. Currently, the fast Fourier transform (FFT) is commonly used to calculate power spectra. However, its spectral leakage problem makes it impossible to thoroughly eliminate radio frequency interference (RFI), which seriously interferes with the extraction of the weak cosmic reionization signal. Polyphase filter bank (PFB) is a technique that divides signals uniformly by frequency and can replace FFT for power spectrum calculation. This paper introduces the basic principle of PFB and its implementation based on Compute Unified Device Architecture (CUDA), compares the performance of PFB and FFT through simulations, and examines performance differences across various PFB orders. The results demonstrate that PFB technology provides flatter passband response, narrower transition bands, and better out-of-band suppression. Finally, by processing observational data from the Tianma Telescope and data generated by low-frequency total power experiments, we verify the superiority of PFB technology, providing an effective solution for spectral analysis in all-sky total power experiments.

**Keywords:** CUDA; polyphase filter bank (PFB); GPU parallel computing; signal processing; polyphase filter; FFT operation

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## 1 Introduction

As the early universe cooled through cosmic expansion, it entered the "Dark Ages" with no luminous objects, only diffuse neutral gas. High-density dark matter aggregates formed dark matter halos that attracted gas to create the first generation of luminous objects. Some of the high-energy photons released by these objects escaped and ionized intergalactic neutral hydrogen. By redshift $z = 6$, intergalactic gas was essentially fully ionized—a process known as "cosmic reionization" [?]. Neutral hydrogen atoms produce the 21 cm emission line, which serves as a crucial probe for studying the cosmic dawn period. However, the neutral hydrogen emission from the cosmic dawn and reionization epoch is extremely weak, five orders of magnitude lower than the foreground dominated by Galactic synchrotron radiation. Consequently, studying and detecting these faint signals presents a formidable challenge. Moreover, within the 50–200 MHz frequency band, radio frequency interference (RFI) from human activities is extremely complex. Therefore, eliminating such interference and extracting the neutral hydrogen 21 cm emission line are essential problems that must be overcome in future studies of early cosmic history and structure evolution.

The Fourier transform (FT) algorithm is one of the important methods in radio astronomical signal processing. For observations with finite duration, the discrete Fourier transform (DFT) is practically implemented through the fast Fourier transform algorithm to efficiently calculate signal spectra. However, the DFT algorithm has two notable drawbacks: (1) frequency leakage, where a single-frequency input signal, particularly when strong, produces responses across multiple frequency points in the spectrum; and (2) scalloping loss, where the frequency response within individual frequency bins obtained through DFT is not flat, resulting in energy loss between different frequency bins [?]. To overcome these limitations and achieve higher-precision spectral results, polyphase filter bank (PFB) technology [?] has been proposed. PFB is an alternative spectral computation method that can effectively address DFT shortcomings by decomposing signals into multiple components and processing each part according to its characteristics. This technology improves data processing effectiveness when handling astronomical data with high spectral quality requirements, offering significant advantages in spectral quality.

The history of PFB architecture dates back to 1973, when Schafer and Rabiner [?] first introduced it in designing speech analysis-synthesis systems. Subsequently, in 1976, Bellanger et al. [?] provided a detailed exposition of the PFB architecture, clarifying its concepts. Although the theoretical foundation of PFB was established early, its application in radio astronomical spectral measurements came relatively late. It was not until 1991, in a NASA mission, that Zimmerman and Gulkis [?] verified that the sidelobe suppression performance of polyphase DFT systems far exceeded that of windowed DFT systems, formally introducing PFB architecture into radio astronomy and providing new perspectives and tools for the field. Entering the 21st century, Bunton [?] further promoted the adoption of PFB in radio astronomy in 2000 by recommending its use in radio interferometer correlator systems—a suggestion that gained widespread recognition and acceptance. As PFB systems became increasingly popular, their applications in radio astronomy expanded, becoming one of the important tools for cosmic research and attracting attention from many domestic researchers. In 2010, Chen Linjie et al. [?] proposed a design scheme based on polyphase filters, implementing signal filtering through polyphase filters, followed by detection, integration control, and finally obtaining spectral intensity. In 2011, Zhu Kai et al. [?] utilized polyphase filter banks for spectral computation. In 2015, Wu Junlin et al. [?] divided a 400 MHz bandwidth into 16 channels of 25 MHz each, implementing a spectrum refinement system with 6,000 channels and 4 kHz frequency resolution for FAST (Five-hundred-meter Aperture Spherical Radio Telescope) neutral hydrogen observations within the Galactic plane. In 2015, Zhao Xin et al. [?] designed and implemented a polyphase filter multi-channel digital terminal based on Hamming windows, applicable for FAST extragalactic neutral hydrogen surveys. In 2016, Zhang Xia et al. [?] studied signal distortion and ultimately reconstructed the true signal. In 2020, Liu Ye et al. [?] developed a digital spectrometer with real-time bandwidth of 10 MHz–2 GHz, completing development and performance testing for both fast scanning and pulse monitoring observation modes. In 2023, Zhang Hailong et al. [?] analyzed PFB frequency characteristics in detail, comparing them with mathematical filter bank (MFB) amplitude-frequency responses, finding that PFB produces flatter passband responses and narrower, steeper transition bands, thereby effectively mitigating spectral leakage problems.

In this work, we employ a frequency range of 50–200 MHz for the digital receiver used in low-frequency all-sky total power experiments to receive and detect cosmic reionization signals. We design and test a prototype program for PFB spectrum generation and processing based on graphics processing unit (GPU). Using this program, we perform spectral analysis on both simulated and real observational data, comparing results with traditional FFT. The results show that our PFB spectrum generation and processing program can effectively suppress frequency leakage, which provides important assistance for removing radio interference signals in low-frequency all-sky total power experiments and subsequent extraction of weak cosmic reionization signals. Section 2 of this paper introduces the principles and structural design of polyphase filter bank technology. Section 3 presents the CUDA-based algorithm for polyphase filter bank technology, analyzes PFB performance through simulated data processing, and compares the advantages and disadvantages of PFB versus traditional FFT in spectral response. Section 4 applies PFB technology to analyze measured and experimental data, verifying its application prospects in low-frequency all-sky total power experiments. Section 5 analyzes the impact of this technology on data processing, provides discussion and summary, and also discusses aspects requiring improvement and enhancement in our work.

## 2 Principle of Polyphase Filter Banks

Polyphase filter bank technology divides an input signal into multiple sub-signals for parallel processing. The digital signal passes through a filter expressed by the formula:

$$y(n) = \sum_{m=0}^{M-1} h(m)x(n-m)$$

where $y(n)$ is the output signal, $h(m)$ are the digital filter coefficients, and $x(n)$ is the input signal. For polyphase filter banks, this is equivalent to shifting the prototype filter spectrum to obtain the corresponding spectral output from the input signal. The output of a single channel is:

$$X_k(n) = \sum_{m=0}^{M-1} x(nD-m)h(m)e^{-jw_k m} = \sum_{m=0}^{M-1} x(nD-m)h(m)W^{-km}$$

where $k = 0, 1, 2, \dots, K-1$, $w_k = 2\pi k/K$, $W_K = e^{j2\pi/K}$, $K$ is the number of channels, and $D$ is the decimation factor. The $k$-th channel possesses bandpass filtering functionality with center frequency shifted to $w_k$ [?].

$$x_i(m) = x(mK-i)$$
$$p_i(m) = h(mK+i)$$

where $i = 0, 1, 2, \dots, K-1$, and $x_i(m)$ is the polyphase component of $x(m)$. If $D = K$, then equation (2) can be expressed as:

$$X_k(n) = \sum_{m=0}^{M-1} x(nD-m)h(m)e^{-j2\pi \frac{k}{K} m} = \sum_{r=0}^{K-1} \sum_{i=0}^{K-1} x(rK-i)h(n-rK+i)e^{j2\pi \frac{k}{K}(rK-i)}$$

$$= \sum_{i=0}^{K-1} \sum_{r=0}^{\infty} x_i(r)p_i(n-r)e^{-j2\pi \frac{k}{K} i} = \sum_{i=0}^{K-1} \left[ \sum_{r=0}^{\infty} x_i(n)p_i(n) \right] e^{-j2\pi \frac{k}{K} i} = \mathrm{DFT}[x_i(n)p_i(n)]$$

From the above derivation, we can conclude that polyphase filter banks can be efficiently implemented using FFT.

The basic principle of polyphase filter banks is illustrated in Figure 1 [Figure 1: see original paper], which shows a polyphase filter bank implementation with filter order $n_{tap} = m$ and number of channels $n_{chan} = N$. On the left, the input signal is sequentially divided into $N$ groups in time domain, each passing through sub-filters. The $N$ group outputs $y(n)$ then undergo $N$-point FFT, with the final output $Y(n)$ being the frequency-decomposed signal.

## 3 CUDA Programming Implementation and Performance Analysis

While polyphase filter banks enhance signal processing precision, they also significantly increase computational complexity and workload. To address this issue, we employ GPU acceleration using CUDA to compile the relevant software.

The algorithm flow for the CUDA-based polyphase filter bank is shown in Figure 2 [Figure 2: see original paper]. Data is transferred via GPU calls, where digital signals are decomposed and parallelly assigned to multiple GPU threads. The input data is a one-dimensional array, which the program organizes into a two-dimensional array based on the number of channels $n_{chan}$. In the GPU, an array of length $n$ is decomposed such that if $n_{chan} = N$, the first $N$ data points serve as the first column, $N + 1$ to $2N$ as the second column, and so on. The first group consists of data points $1, N+1, 2N+1, ...$, and similarly for other channel data distributions. Multiple cores are invoked to perform FIR and FFT on each data group, with final results returned to the central processing unit (CPU). In CUDA, the `cufftExecR2C()` function from the cuFFT library enables efficient parallel FFT computation.

In this software, we designed a prototype filter frequency response (shown in Figure 3 [Figure 3: see original paper]) featuring moderate main lobe width and roll-off characteristics with low sidelobe levels, demonstrating good frequency domain properties.

To verify the software' s effectiveness, we performed spectral analysis on a simulated signal with sampling rate 128 S/s and frequency 60 Hz using both this software and FFT. The results in Figure 4 [Figure 4: see original paper] show the signal at 60 Hz on the frequency axis, confirming that the software successfully implements spectral analysis. The asymmetric frequency response of PFB spectral analysis is primarily due to the use of real-to-complex FFT transform type in CUDA' s cuFFT package, where the effective output bits are half of the input.

With the software running successfully, we conducted the following experiment: using digital signal length $n = 32,768$, filter order $n_{tap} = 8$, number of channels $n_{chan} = 1,024$, we generated 61 sets of simulated data with 0.05 Hz steps across the frequency range 59.85–60.15 Hz for spectral analysis. We plotted the frequency response of PFB within a single channel and compared it with FFT.

Figure 5 [Figure 5: see original paper] shows the single-channel response values. In this simulation, the channel bandwidth is 0.125 Hz. As illustrated, the 1 dB bandwidth is 0.08 Hz for FFT and 0.1 Hz for PFB; the 20 dB bandwidth is 0.22 Hz for FFT and 0.15 Hz for PFB. This demonstrates that PFB achieves narrower transition bands compared to FFT.

Additionally, after varying the filter order in PFB (by adjusting $n_{tap}$ to 4, 8, 12, and 16), we performed spectral analysis on simulated data and compared the effects. The results in Figure 6 [Figure 6: see original paper] show that as filter order increases, the effective bandwidth becomes wider, the transition band becomes narrower, and out-of-band suppression increases (the red dashed line indicates the cutoff frequency).

## 4 Experimental and Observational Data Processing

We processed observational data from the 65 m Tianma Radio Telescope of the Shanghai Astronomical Observatory, Chinese Academy of Sciences. We selected S-band observation data with a channel center frequency of 2,256 MHz and compared it with FFT spectra, as shown in Figure 7 [Figure 7: see original paper]. We extracted the relatively flat frequency portion from 11–14 MHz (corresponding to actual frequencies of $2,256-32+(11–14)$ MHz) and calculated its root mean square (RMS) value. Precise measurements yielded an RMS of 163.23 for FFT and 163.08 for PFB. Figure 8 [Figure 8: see original paper] shows an enlarged view near 24 MHz in Figure 7. In the range 24.60–24.75 MHz, PFB exhibits sharper peaks and lower troughs than FFT, demonstrating superior spectral analysis capability.

Additionally, we processed data generated by the low-frequency total power experiment digital receiver with a sampling rate of 480 MHz. As shown in Figure 9 [Figure 9: see original paper], within the 90–100 MHz band, PFB achieved an RMS of 31.84 compared to 21.48 for FFT. Notably, at the 10 MHz main peak, PFB shows sharper response with steeper sides and more pronounced suppression. Compared to FFT technology, PFB technology in low-frequency all-sky total power experiments can more easily remove RFI signals resembling point spectra, facilitating subsequent extraction of weak 21 cm signals.

## 5 Summary and Outlook

This paper develops PFB-related software using CUDA for all-sky total power experiments. Simulation analysis demonstrates the software's performance: narrow transition bands, flat passband response, and high out-of-band suppression. We then processed measured and experimental data, verifying the method' s application prospects in all-sky total power spectrum experiments.

Currently, the software is only used for limited signal simulation and partial real radio signals. The next step will involve processing large volumes of radio signals to verify its performance in practical applications. As radio astronomers need to process increasingly large amounts of radio data, we believe that utilizing PFB technology for spectral analysis will extract more scientific information and make contributions to the future development of radio astronomy.

## References

[1] Zhang Xueying, Guo Quan, Zheng Qian, et al. *Acta Astronomica Sinica*, 2023, 64(1): 96
[2] Zhang Xianchao, Wu Jigang, Jiang Zengrong, et al. *Acta Electronica Sinica*,

2000, 28(5): 105
[3] Zhang Weiliang, Zhang Yu, Yang Zaichu, et al. *Systems Engineering and Electronics*, 2009, 31(8): 1819
[4] Wu Yanbin. *Technology Wind*, 2009, 9(3): 63
[5] Schafer R, Rabiner L. *IEEE Transactions on Audio and Electroacoustics*, 1973, 21(3): 165
[6] Bellanger M, Bonnerot G, Coudreuse M. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 1976, 24(2): 109
[7] Zimmerman G A, Gulkis S. *The Telecommunications and Data Acquisition Report*, No.15. Pasadena, California: JPL, Calif of Tech, 1991: 141
[8] John Bunton. https://library.nrao.edu/public/memos/alma/memo342.pdf, 2025
[9] Chen Linjie, Yan Yihua, Liu Fei, et al. *Astronomical Research & Technology*, 2010, 7(2): 89
[10] Zhu Kai, Gan Hengqian, Zhu Yan, et al. *Astronomical Research & Technology*, 2011, 8(1): 81
[11] Wu Junlin, Jin Chenjin, Zhu Yan, et al. *Astronomical Research & Technology*, 2015, 12(4): 473
[12] Zhao Xin, Jin Chenjin, Zhu Yan, et al. *Astronomical Research & Technology*, 2015, 12(4): 495
[13] Zhang Xia, Yu Xinying, Duan Ran, et al. *Progress in Astronomy*, 2016, 34(2): 249
[14] Liu Ye, Liu Qi, Li Jian, et al. *Astronomical Research & Technology*, 2020, 17(4): 429
[15] Zhang Hailong, Zhang Meng, Zhang Yazhou, et al. *Journal of Jilin University (Engineering and Technology Edition)*, 2023, 53(8): 2388
[16] Harris F J, Dick C, Rice M. *IEEE Transactions on Microwave Theory and Techniques*, 2003, 51(4): 1395

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