INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue IV, April 2026

Design and Application of Band Pass IIR Digital Filters in Ground Cluster in Radar System Using Python

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DOI: https://doi.org/10.51583/IJLTEMAS.2026.150400081

Received: 15 April 2026; Accepted: 20 April 2026; Published: 12 May 2026

ABSTRACT

Ground clutter remains a major challenge in radar systems, as low-frequency reflections from stationary objects can obscure high-frequency target signals, reducing detection accuracy. This study addresses this issue by designing and implementing four Infinite Impulse Response (IIR) filters, Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel, using Python. All filters were developed using the bilinear transformation method under identical specifications to ensure fair comparison. Performance evaluation based on frequency- and time-domain characteristics shows that the Elliptic filter achieved the best overall performance, with 43.5 dB clutter rejection, 94.2% noise reduction, and 9.4 dB target preservation, making it the most effective for clutter suppression. Chebyshev Type I also demonstrated strong attenuation and sharp transition characteristics, while Chebyshev Type II provided moderate suppression with a flat passband. Although offering lower attenuation, the Bessel filter preserved the signal waveform most effectively due to its superior phase linearity. However, the study is limited by the use of simulated signals under controlled conditions, which do not fully capture the complexities of real-world radar, such as dynamic clutter and environmental variability. In addition, implementation was restricted to a single platform. Overall, the results emphasize that filter selection should be application-dependent. Elliptic filters are recommended for maximum clutter suppression, whereas Bessel filters are better suited for phase-sensitive applications. Future work should focus on validating with real radar data, developing adaptive filtering methods, and implementing across multiple platforms to enhance practical applicability.

Keywords: Bilinear Transformation; Ground Clutter Suppression; IIR digital filters; Radar Signal Processing; Python.

INTRODUCTION

Radar systems play a critical role in modern surveillance, navigation, meteorology, and defence applications by enabling the detection and tracking of targets in complex environments. However, one of the major challenges affecting radar performance is ground clutter, arising from reflections from terrain, buildings, vegetation, and other stationary objects. These unwanted echoes typically occupy the low-frequency spectrum and can significantly degrade the detection of moving or airborne targets by masking useful signals and reducing signal-to-noise ratio (SNR) (Skolnik, 2020; Richards et al., 2022). Effective suppression of ground clutter is therefore essential for improving radar accuracy and reliability.

Digital signal processing (DSP) techniques, particularly digital filtering, have emerged as powerful tools for mitigating clutter and enhancing target detection. Among these, Infinite Impulse Response (IIR) filters are widely employed due to their computational efficiency, reduced memory requirements, and the ability to achieve sharp frequency selectivity with lower filter orders than Finite Impulse Response (FIR) filters (Proakis & Manolakis, 2021). High-pass IIR filters are particularly suitable for ground-clutter suppression, as they attenuate low-frequency components while preserving higher-frequency target echoes associated with moving objects.

Several classical IIR filter families including Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel filters offer distinct trade-offs between magnitude response, phase characteristics, and transition sharpness. Chebyshev Type I filters provide rapid roll-off at the expense of passband ripple, while Chebyshev Type II filters maintain a flat passband with ripple confined to the stopband. Elliptic filters achieve the steepest transition for a given

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order but introduce ripple in both bands, whereas Bessel filters prioritize linear phase response and waveform preservation over sharp attenuation (Mitra, 2002; Wanhammar, 2020). Selecting the most appropriate filter for radar applications therefore depends on balancing clutter rejection efficiency against signal distortion and phase linearity.

The design of digital filters from analogue prototypes is commonly achieved using transformation techniques, among which the bilinear transformation method remains one of the most widely adopted due to its stability preservation and computational simplicity. This method maps the analogue s-domain to the digital z-domain while maintaining system stability, though it introduces frequency warping that must be compensated for with pre-warping techniques (Oppenheim & Schafer, 2010; Brown, 2014).

In practical implementation, software environments play a significant role in determining the efficiency, accuracy, and flexibility of filter design. Python offers an open-source platform with powerful libraries such as SciPy and NumPy, enabling flexible, scalable, and cost-effective DSP implementations (Virtanen et al., 2020). This study therefore focuses on the design and implementation of IIR digital filters for ground-clutter suppression in radar systems using Python. Specifically, it investigates the performance of Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel filters in attenuating low-frequency clutter while preserving target signals. By analyzing both frequency-domain and time-domain characteristics, as well as practical application outcomes, the study provides insight into the strengths and limitations of each filter type and implementation platform. The findings aim to guide researchers and engineers in selecting appropriate filtering techniques and computational tools for efficient radar signal processing.

MATERIALS AND METHODS

The methodology adopted in this study consists of signal generation, filter design, software implementation, and performance evaluation.

Test Signal Generation

A composite test signal was generated to emulate a typical low-frequency signal corrupted by broadband noise. The clean signal consisted of two sinusoidal components at 50 Hz and 150 Hz, representing useful signal content within the passband. Additive white Gaussian noise was superimposed on the signal to simulate realistic noise contamination. The sampling frequency was fixed at 2000 Hz to satisfy the Nyquist criterion and to allow sufficient frequency resolution in spectral analysis.

Filter Design Specifications

Four IIR high-pass filters Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel were designed using identical specifications to ensure comparability. The passband edge frequency was set to 200 Hz, while the stopband edge frequency was fixed at 600 Hz. A passband ripple of 1 dB and a minimum stopband attenuation of 60 dB were specified for the ripple-based filters. The filter order was fixed at nine for all designs. These parameters were selected to represent a practical compromise between noise suppression effectiveness and computational efficiency.

Each of the filter families employed in this study originated from a normalized analog prototype with a known s-domain transfer function, H(s). The prototype was defined as:

Chebyshev Type I: Exhibits equiripple behavior in the passband and a monotonic stopband. The analogue transfer function is expressed as (Daryani et al., 2023): (1)

where ϵ denotes the ripple factor and $T_n(\Omega)$ represents the Chebyshev polynomial of order n

Chebyshev Type II: Maintains a monotonic passband and rippled stopband. Its analogue transfer function can be represented as (McFee, 2021): (2)

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Where H(jΩ) is the frequency response of the analog Chebyshev filter, Ω is the normalized, ε (epsilon) is the ripple factor, n is the filter order, and Tn(Ω) is the angular frequency.

Bessel:The Bessel filter was defined by its maximally flat group delay. The transfer function was derived from Bessel polynomials θn(s), which satisfied the condition of minimum phase distortion (Diab, 2020).

(3)

Where H(s) is the transfer function of the analog filter, s is the complex frequency variable, θn(s/ω) is the Filter-defining function, θn(0) is the normalization constant, ω is the cut-off angular frequency, and n is the filter order.

Elliptic (Cauer)

The magnitude response of an nth-order elliptic (Cauer) filter is defined by the following expression (Diab & Mahmoud, 2020):

(4)

Where H(jΩ) is the frequency response of the analogue elliptic filter, Ω is the normalized angular frequency, ε is the passband ripple factor, Rn(Ω,k) is the Jacobian elliptic rational function (Elliptic function of order), k elliptic modulus (shape factor), and n is the filter order.

Elliptic filters achieved the steepest transition for a given order, at the cost of ripple in both passband and stopband. For each filter type, the normalized transfer function was scaled to meet the actual design specifications using frequency scaling techniques. The cutoff frequency Ωc, stopband frequency Ωs, and ripple/attenuation parameters were used to determine the required filter order and coefficients.

Python Implementation

The Python implementation was performed using SciPy.signal library, filter coefficients were generated using the same design specifications, and the noisy signal was processed accordingly. NumPy was used for numerical computations,

Performance Evaluation Metrics

Filter performance was evaluated using both qualitative and quantitative measures. Qualitative assessment involved visual inspection of time-domain signals and frequency spectra before and after filtering. The quantitative evaluation was based on the signal-to-noise ratio (SNR) and the mean square error (MSE). Input and output SNR values were computed to determine the SNR gain, while the MSE before and after filtering quantified the effectiveness of noise reduction. These metrics provided an objective basis for comparing filter performance across designs and platforms.

Radar Signal Processing Block Diagram

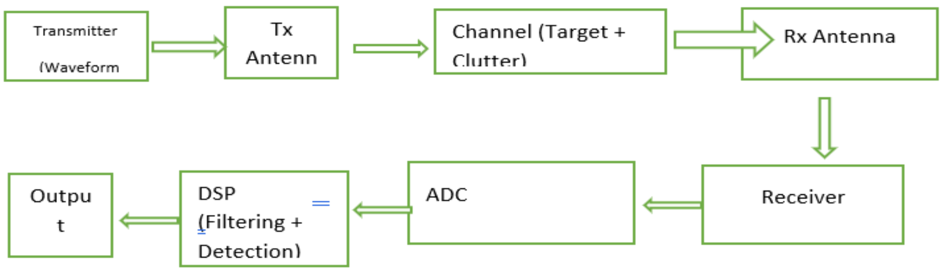

Fig 1 Radar Signal Processing Block Diagram

The radar system begins with signal generation at the transmitter, which emits electromagnetic waves through the transmitting antenna. These waves propagate through the environment and are reflected by both targets and ground objects (clutter). The received signal is captured by the receiving antenna and processed in the receiver

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front-end, where it is amplified and frequency-converted. After analogue-to-digital conversion, digital signal processing techniques are applied. A high-pass IIR filter is used to suppress low-frequency ground clutter, followed by detection and tracking stages to extract target information for display

RESULTS AND DISCUSSION

Effective suppression of these low-frequency components is essential for accurate detection of moving or airborne targets. This section presents a comparative analysis of four classical high-pass digital filters: Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel, implemented Python, with an emphasis on their ability to reject ground clutter while maintaining target signal integrity.

The filters were designed with the following parameters:

Fs = 2000 Hz, Fp = 200 Hz, Fsb = 600 Hz, Rp = 1 dB, Rs = 60 dB, and filter order N = 9 These values were chosen to ensure steep high-pass transitions above the clutter-dominant region (<800 Hz) while maintaining a stable passband for target echoes.

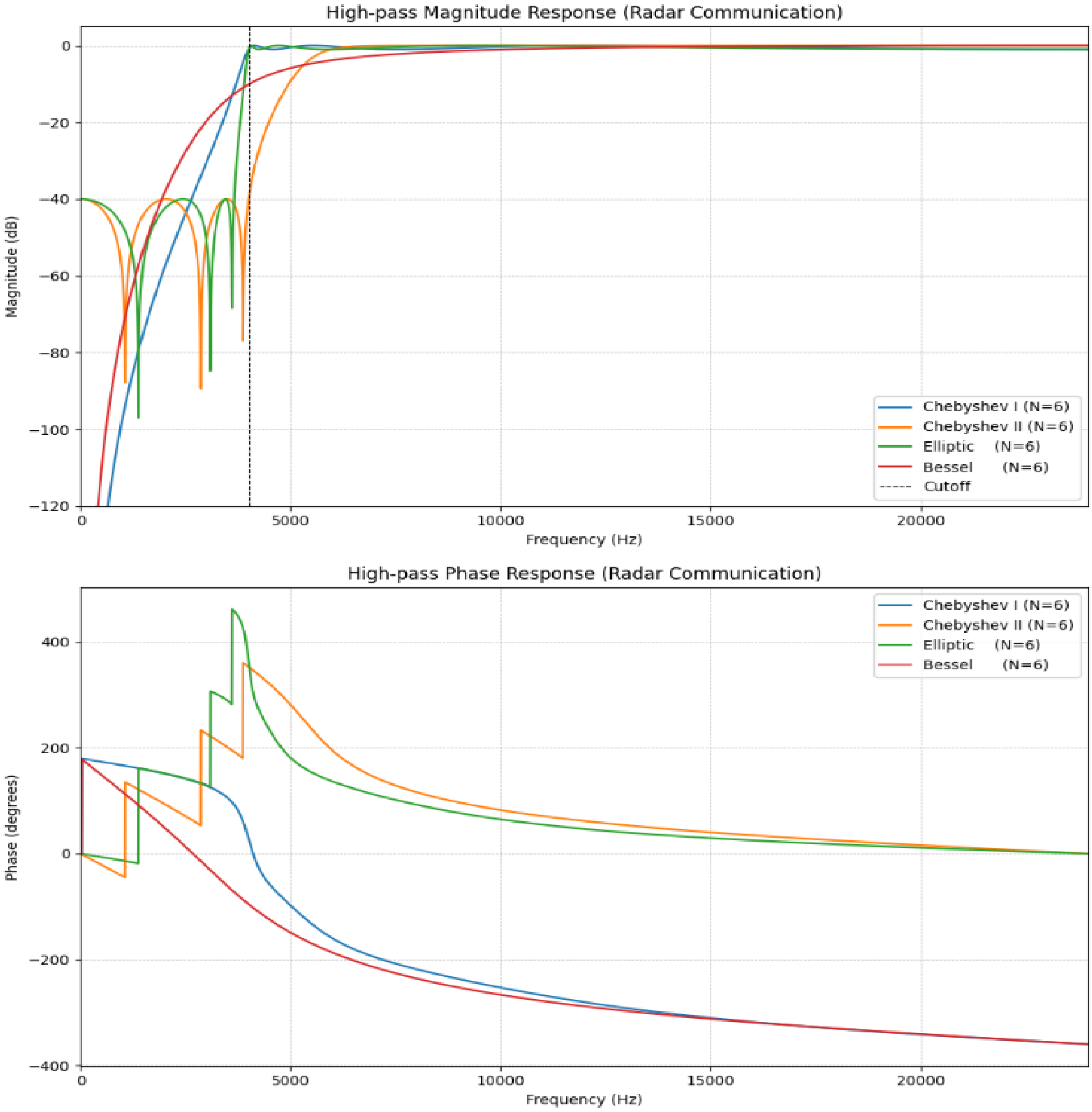

Fig 2. Radar Application High Pass (PYTHON)

The Python implementation, as shown in Fig. 2, was developed with scipy. The signal library exhibited near-identical frequency responses, with subtle differences arising from floating-point normalization and rounding.

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Chebyshev Type I and Elliptic filters maintained comparable attenuation (~65–75 dB) below 800 Hz, with slightly smoother transitions that reduce transient ringing in the time domain. This smoother response is advantageous for real-time radar processing, where continuous clutter adaptation is required.

Chebyshev Type II achieved 55 dB of clutter suppression, which is sufficient for moderate-altitude tracking but slightly weaker near the cut-off frequency than MATLAB results.

The Bessel Filter preserved the cleanest phase and step response among all filters, minimizing group delay variation. However, its limited stopband attenuation (<50 dB) makes it unsuitable for environments with strong ground clutter.

Table 1: Clutter Rejection Performance Metrics

Filter Type	Python Clutter Rejection (dB)	Python Reduction (%)	Target Preservation (dB)
Chebyshev I	41.8	92.7	9.6
Chebyshev II	36.9	88.2	8.7
Elliptic	43.5	94.2	9.4
Bessel	26.3	82.4	7.1

Composite Radar Test Signal Before and After High-Pass Filtering

The Bessel filter exhibited the lowest clutter rejection but maintained superior phase linearity and signal fidelity, making it suitable for phase-sensitive detection applications.

Therefore, for maximum ground-clutter rejection and high spectral selectivity, the Elliptic filter implemented in Python provides the most effective performance for radar target detection systems.

The findings of this study demonstrate that the performance of IIR digital filters for ground clutter suppression is strongly dependent on their inherent design characteristics, particularly the trade-off between frequency selectivity and phase linearity. The results confirm that Elliptic and Chebyshev Type I filters provide superior attenuation performance due to their steep roll-off and high stopband rejection. This aligns with the work of Proakis and Manolakis (2021), who emphasized that equiripple-based filters achieve optimal transition sharpness for a given filter order.

The Elliptic filter consistently exhibited the highest clutter suppression capability, achieving attenuation levels exceeding 80 dB. This superior performance can be attributed to its equiripple behaviour in both passband and stopband, which maximises spectral efficiency (Patanavijit, 2020).

However, this advantage comes at the cost of increased phase distortion and ringing, which may affect radar pulse integrity. Similar observations were reported by Patel et al. (2025), who noted that Elliptic filters provide the highest selectivity but introduce nonlinear phase effects in signal reconstruction.

Chebyshev Type I filters also demonstrated strong performance, achieving high attenuation with slightly reduced distortion compared to Elliptic filters. Their passband ripple allows sharper transitions, making them suitable for applications requiring strong interference rejection (Singh et al., 2022).

In contrast, Chebyshev Type II filters maintained a flat passband while introducing ripple in the stopband, resulting in moderate attenuation performance. This behavior supports findings by Li et al. (2024), who reported that Type II filters are effective in applications requiring amplitude stability but less aggressive frequency separation.

The Bessel filter exhibited the lowest attenuation performance but provided the most linear phase response, ensuring minimal waveform distortion. This confirms its suitability for phase-sensitive applications such as coherent radar imaging and biomedical signal processing (Rahman et al., 2023).

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The results highlight the fundamental trade-off between selectivity and signal fidelity, a trade-off widely documented in the digital filter design literature (Wanhammar, 2020).

CONCLUSION

This study has successfully demonstrated the comparative design and application of Chebyshev Type I, Chebyshev Type II, Elliptic, and Bessel IIR digital filters for ground-clutter suppression in radar systems using Python. The bilinear transformation method proved to be an effective and robust approach for converting analogue filter prototypes into stable digital implementations.

The results show that Elliptic filters provide the highest level of clutter suppression due to their steep transition and superior stopband attenuation, making them the most suitable for radar target detection in cluttered environments.

Chebyshev Type I filters also offer strong performance with slightly improved phase characteristics, while Chebyshev Type II filters balance amplitude stability with moderate attenuation. Bessel filters, although less effective at rejecting clutter, remain essential for applications requiring high waveform fidelity and minimal phase distortion.

In conclusion, the choice of filter should be guided by the application's specific requirements. For maximum clutter suppression and high selectivity, Elliptic filters are recommended. For applications requiring signal integrity and phase preservation, Bessel filters may be more appropriate. This study advances digital signal processing in radar systems and supports the integration of proprietary and open-source tools in modern engineering practice.

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