Comparative Analysis of Noise-Reduction Filters for Low-cost Radio Telescope Data

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Abstract. In observational astronomy, the correct extraction of solar radio signals is the major requirement, but such data obtained through low-budget radio telescopes are often deteriorated by strong narrowband interference. The radio telescope systems, which are usually designed with easily available components such as parabolic dish antennas, connecting cables, low-cost satellite meters, and spectrum analyzers, have inadequate shielding for signals and hence remain extremely susceptible to additional noise. Regarding the above-mentioned realistic constraints, the presented study attempts a number of widely used signal filtering methods, including lowpass, Chebyshev, Gaussian, median, bandstop, and notch filters, with simulation-based investigations using software and comparison of filters was carried out by employing MSE, SNR, and correlation coefficient as evaluation parameters. Based on the presented analysis, it was found that the notch filter showed the best performance among the above-mentioned approaches, since it attained an SNR value of 46.10 dB while offering the minimum MSE of 0.100035 along with a correlation coefficient which is very close to unity (0.9992). These values demonstrate that the notch filter acts effectively to suppress the undesired interference while preserving the intrinsic characteristics of the radio signal coming from the Sun. It is a unique approach to develop a less expensive and efficient filtering technique for low-budget radio telescope operating within urban or semi-urban areas with generally higher levels of interference.

1 Introduction

The accurate detection and analysis of solar radio emissions form a crucial part of observational astronomy and provide meaningful information about solar activity, space weather conditions, and their specific effects on Earth. Obtaining any reliable solar radio data is problematic, mostly if the research involves the use of low-cost radio telescopes and ground-based facilities. These low-cost systems, typically consisting of relatively inexpensive components including parabolic dish antennas, connecting cables, satellite meters, and spectrum analysers, are easily interfered with by narrowband interference due to electronic devices in the general vicinity, surrounding communication systems, and background environmental noise. This interferes with the quality of the signals received and reduces the accuracy and scientific usefulness of the observation.

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Various filtering methods have been explored to enhance the clarity of the desired signal and suppress unwanted noise in radio astronomy. However, filter performance is usually highly dependent on the type and characteristics of interference within the observational environment. Identifying a suitable filtering method is one of the research challenges yet to be undertaken for low-cost radio telescopes.

This study tries to solve the problem by a systematic comparative evaluation of the most common digital filters used in practice, such as lowpass, Chebyshev, Gaussian, median, bandstop, and notch filters. By software-based simulations and by using quantitative performance metrics, including Correlation coefficient, Signal to Noise ratio (SNR), Mean Squared Error (MSE) [9], this research aims to determine the best filtering technique to improve the quality of solar radio observations obtained from low-cost telescopes.

This work focuses on the combines software-based simulations and a set of quantitative performance metrics, such as SNR, MSE, and the Correlation Coefficient. These metrics altogether describe signal clarity, reconstructive accuracy, and waveform similarities and are thus useful to obtain a broad view of filters' performance. In-depth comparison is therefore undertaken in the research, evaluating thoroughly the data to reach a conclusion on which filtering technique gave the best improvement in signal quality, hence proposing more accurate and reliable solar radio observations, especially in resource-constrained or interference-prone environments.

The novelty of the presented research is the systematic comparative analysis it performs using several filtering techniques on low-cost solar radio telescopes under realistic narrowband interference conditions. By employing three quantitative evaluation metrics-MSE, SNR, and correlation coefficient- proposing a very cost-effective and practical solution to improve the quality of the solar radio signals in resource-limited observational setups. This would be a unique approach that will enable the low-cost radio telescope to process and retrieve high-quality solar radio signals efficiently, hence a convenient solution for resource-constrained observational setups.

2 Related Work

Previous research made use of commercial television dish antennas available in the market, specifically the SUN DIRECT HD STC 11-04 model, which works within the frequency band of 10.7 GHz to 18 GHz. In typical radio telescopes, a parabolic dish is usually used to focus the incoming radio waves. These radio waves can then be received at the focal point of the dish or reflected back through the middle of the dish towards the focal point [2].

The radio telescope consists of a parabolic dish antenna along with a Low Noise Block (LNB), satellite finder, and receiver. Despite various shortcomings of less sensitivity towards orientations and accuracy in measurement, it is capable of detecting solar radiation and blackbody radiation. The orientations are possible for observing radio sources in an automatic way or manual way; the satellite finder helps in receiving signals for further recording [3]. This study showed that tracking and analyzing solar radio emissions is possible with affordable radio telescope setups, but highlighted the significant challenge posed by narrowband interference in urban areas [4]. Due to the interference of other radio signals the received signal was very noisy. There are several denoising filters like lowpass, Chebyshev, Gaussian, median, bandstop, and notch filters.

Chebyshev filters fall into type I and Type II filters as per their frequency response characteristics, fluctuating in the frequency response amplitude of either the passband or the stopband. Such filters can allow sharper transitions in the stop band along with ripples in the pass band. In general, they can be applied where stopband attenuation at any cost, even of the ripple in the passband is required. They find their application in radio communications systems, audio system, and instrumentation [5]. In case of The Gaussian filtering is one of the most important linear smoothing filters, which removes Gaussian noise from the profile and is very common in the noise reduction process. Thus, Gaussian filter is an excellent filter for generic applications, and at present, it is a standard process for separating the roughness and waviness component from the primary surface.

Following the filtering process, the signal to noise ratio (SNR) is enhanced without distorting the desired signal. The majority of existing optimal filters, for instance, Wiener filter and subspace transform methods, have been derived based on mean square error (MSE) formulations. However, with MSE formulation, a variety of properties associated with existing optimal filters meant to suppress noises will not be observable [7].

Although low-cost radio telescopes were developed in earlier research works, the signal processing aspect was not emphasized through comparative analysis. Therefore, this research specifically focuses on not only developing a low-cost radio telescope but also performing signal processing with a comparative analysis based on SNR, MSE, and correlation coefficient to identify which filter is most effective in reducing noise.

3 Block Diagram

Here, dish antennas, cables, cheap satellite meters (SF-720), and spectrum analysers (OWON Model: XSA 1036-TG) that can easily be accessed are used to construct a radio telescope setup.

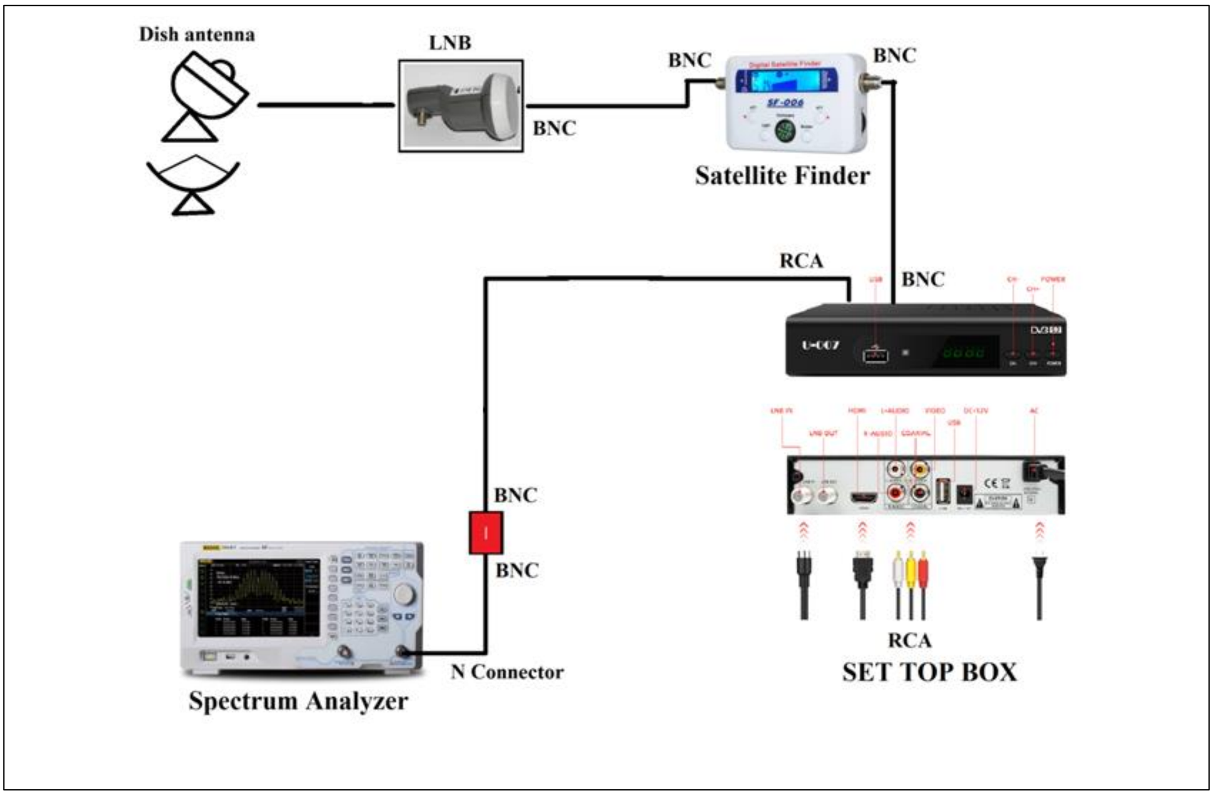

Fig-1. Block Diagram of radio telescope setup

Fig. (1) represents the block diagram of the setup [4]. TATA Sky Dish antenna [14] was employed as a parabolic reflector antenna in the proposed design. This parabolic reflector antenna works on the Ku band (12-18 GHz), receiving the radio signals. Further, the signal is passed on to the Low Noise Block amplifier (LNB), which is linked with the feed part of the antenna. It acts as the low noise amplifier because it amplifies the incoming signal without adding noise to it. The coaxial cable sections are called BNC (Bayonet Neill–Concelman) connectors. After passing the signal through a digital satellite finder that assists in determining the signal strength, the antenna orientation is adjusted to obtain the strongest possible signal. For instance, the antenna is aimed at the Sun during signal reception, and its elevation is changed in accordance with the satellite finder. Additionally, the LNB down-converts radio signals to the intermediate frequency (IF) and removes undesired frequencies. For the signal to be compatible with other signal processing devices, this down conversion is necessary. The LNB frequency in the KU-band usually ranges from 10.7 to 12.75 GHz. It is possible to convert the radio signals to the 950–1950 MHz frequency range. Similarly, the satellite finder device is employed to ensure that the LNB is receiving radio waves or not. Certain satellite finder devices could also be employed for an approximation of the signal strength. The down-converted signals in the range of 950-1950 MHz carry information from radio waves sent by the Sun, other planets, or any other source of radio waves. The output signal from the set-top box comprises both the audio signal and the video signal. The particular signal is transmitted to the Spectrum Analyzer. For the proposed radio telescope system, an OWON Model: XSA 1036-TG spectrum analyzer is used, which ranges from 9 KHz to 3.6 GHz. The spectrum is observed in detail, and the frequency components after down-conversion or even after 1.9 GHz are analyzed.

4 Data Collection Methods

The data has been collected using two approaches to examine the radio telescope performance. In the first technique, at a fixed time on a specific date, the signal spectrum is received at various angles of the radio antenna. For the second technique, at a specific angle, the spectrum of the signal is received at varied times. As the sun is the closest celestial object primarily Sun's signal was captured at various angle of inclination. In this study, the signal recorded at an inclination angle of 90° at 12:30 PM was selected for comparative filter analysis, as the signal power attains its maximum at this specific time and angle of inclination.

Fig-2. Radio telescope at angle of inclination 90°

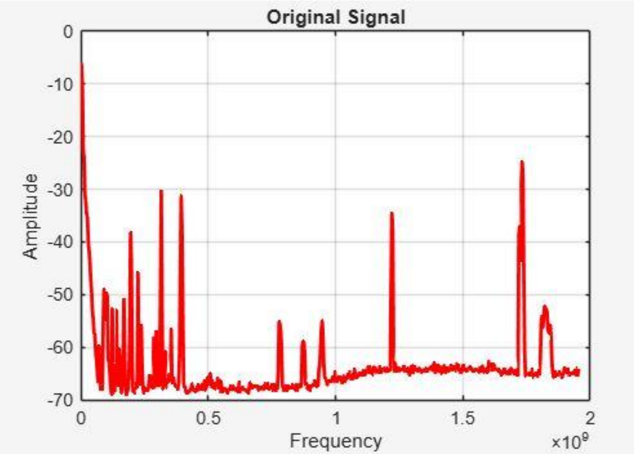

Fig-3. Received signal at angle of inclination 90°

There were multiple peaks of the received signal; however, due to closeness to the Sun, it is believed to mostly represent the signal from the Sun. The received signal was very noisy due to the narrowband interference is caused by artificial sources like AM/ FM transmitter, TV broadcast transmitter, mobile phone towers, satellite communication signals. Therefore, various filters are used here to enhance the quality of the signal.

5 Filters Used

5.1 Low-pass filter:

First, a **low pass filter** was applied to the noisy solar radio signal received by radio telescope. Low pass filtering forms a critical step in the processing of solar radio signals because it serves to remove high-frequency noise selectively, ensuring preservation of low-frequency components that provide useful information. This enhances SNR, suppresses distortion and allows better solar feature detection; hence, it is an important technique in the analysis for the meaningful extraction of data from all types of noisy solar radio signals. The frequency response of an ideal low-pass filter with cut-off frequency fc, [8] is in Eq. [4]:

$$H(f)=\begin{cases} 1, & |f| \leq f_c \\ 0, & |f| > f_c \end{cases} \qquad \text{……………..[4]}$$

5.2 Chebyshev filter:

A Chebyshev filter is important in the processing of solar radio signals since it can provide sharp frequency cutoffs, high stopband attenuation, and hence suppress complex high-frequency interference effectively, while retaining the key characteristics of the solar emission. A Chebyshev Type-I filter is employed in this work.

The magnitude response [15] is in Eq.[5]:

$$|H(f)|^2 = \frac{1}{1 + \epsilon^2 \, {T_n}^2\left(\frac{f}{f_c}\right)} \qquad \text{……………………[5]}$$

Where,

n= filter order

$\in$ = ripple factor

$T_n(x)$= Chebyshev polynomial of order n

f_c= cut-off frequency

5.3 Gaussian filter:

The Gaussian filter is very important in the processing of solar radio signals, given that it realizes a smooth denoising without introducing distortion and maintains key solar features, hence improving scientific accuracy in observations. In particular, such a filter will be very effective in the case of weak and noisy signals that low-cost radio telescope systems usually acquire. The Gaussian filter is unique since its Fourier transform is also Gaussian. The frequency response is in Eq.[6]-

$H(f)= \exp(-2\pi^2\sigma^2f^2)$………………..[6]

Where,

H(f)= frequency response

f= frequency

5.4 Median filter:

The median filter works effectively in such conditions and is therefore important in the processing of solar radio signals as it removes impulse noise and sharp disturbances without compromising actual solar features, homogenizes man-made interference, and produces clean, reliable signals for further processing.

For a discrete time signal x(n), the median filtered output y(n) is [10] in Eq.[7]-

$y(n)= \text{median}\{x(n-k), x(n-k+1),……, x(n),….,x(n+k)\}$……………[7]

Where:

y(n)= output of the median filter

x(n)= input signal

2k+1= size of the sliding window

“median” means the middle value when the samples in the window are sorted in ascending order.

5.5 Bandstop filter:

The Bandstop filter removes a narrow band of RFI (Radio Frequency Interference) and harmonic noise, preserves a substantial part of a solar spectrum, improves SNR and clarity of signals, minimizes distortion of scientific measurements, and finds application in an environment where noise [13] and interferences are present.

The ideal bandstop filter has the following frequency response in Eq.[8]:

$$H(f) = \begin{cases} 1 & 0 \le |f| < f_1 \\ 0 & f_1 \le |f| \le f_2 \\ 1 & |f| > f_2 \end{cases} \qquad ……………………[8]$$

Where:

H(f)= frequency response

f1= lower cut-off of the rejected band

f2 = upper cut-off of the rejected band

Which means,

•frequencies inside [f1, f2] are removed.

•frequencies outside are preserved.

5.6 Notch filter:

The notch filter effectively suppresses the strong, narrowband interference signals and retains the broadband characteristics of solar emissions. Thus, it leads to an improved SNR with the retention of true signal characteristics, enhances the detection of weak features with minimal distortion [12]. Contrarily, notch filter removes very narrow frequency range whereas bandstop filter removes wide frequency range. So that bandstop filter reduces energy from the original signal if useful components lie in the removed band.

Frequency response is in Eq. [9]-:

$$H(s) = \frac{s^2 + w_0{}^2}{s^2 + \frac{w_0}{Q}s + w_0{}^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots[9]$$

Where,

w_0= notch (rejected) angular frequency

Q= quality factor

s= complex frequency variable

All these filters efficiently reduce the noise but in this research work, performance metrics have been used to mathematically demonstrate which filter is most effective in reducing noise from the radio signal.

6 Performance metrics used

Here in this analysis, **Signal to Noise Ratio (SNR)** measurements, **Mean Squared Error (MSE)** calculations, and calculation of **correlation coefficient** have been used collectively to assess objectively the efficacy of digital filtering methods used in improving sun radio signals. Every parameter used in this analysis measures a different parameter of a filtered signal.

The SNR, or the Signal-to-noise Ratio, has considerable significance as it is the measure of the clarity of a signal with respect to noise: it enables one to make effective detection, measurement, and comparison-very important for faint astronomical signals such as solar radio waves or any other radio signals**.** Signal-to-Noise Ratio is expressed in Eq. [1]

$$\mathrm{SNR}_{\mathrm{dB}} = 10\log_{10}(\frac{\sum_n x(n)^2}{\sum_n n(n)^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots[1]$$

Where:

x(n)= filtered signal

n(n)= residual noise

A high SNR indicates a signal that is stronger relative to the noise; this consequently guarantees that there would be higher clarity, fidelity, or a truer representation of the original signal. It is expressed in Decibel (dB).

The **MSE** is important because it is a measure of the total error introduced in filtering or processing. A low MSE means that the signal has been more accurately reconstructed, there is less distortion, and the filter is performing better. It is thus a very important metric in determining the quality and efficiency of signal processing techniques**.** MSE [11] is expressed in Eq. [2]-

MSE= $\frac{1}{N}\sum_{n=1}^{N}(x(n)-\hat{x}(n))^2$…………………………..[2]

Where:

N= total number of samples

$x(n)$=Original signal

$\hat{x}(n)$= Estimated signal or filtered signal

The squared term measures the error at each sample, and the mean gives the overall average error.

It is a significant **correlation coefficient** [14] since it measures the degree to which a filtered signal maintains the shape of the original waveform irrelevant to changes in amplitude. A correlation coefficient close to 1 represents excellent structural precision, making it an essential factor to measure filter performance and signal integrity. It is expressed in Eq. (3)-

r= $\frac{\sum_{n=1}^{N}(x(n)-\bar{x})(\hat{x}(n)-\bar{\hat{x}})}{\sqrt{\sum_{n=1}^{N}(x(n)-\bar{x})^2}\sqrt{\sum_{n=1}^{N}(\hat{x}(n)-\bar{\hat{x}})}^2}$…………………………[3]

where,

N= number of samples

$\bar{x}=\frac{1}{N}\sum x(n)$ mean of the original signal

$\bar{\hat{x}}=\frac{1}{N}\sum \hat{x}(n)$ mean of the filtered signal

The numerator measures joint variation.

The denominator normalizes by the individual variances.

7 Results and Discussion

7.1 Output response of Low-pass filter:

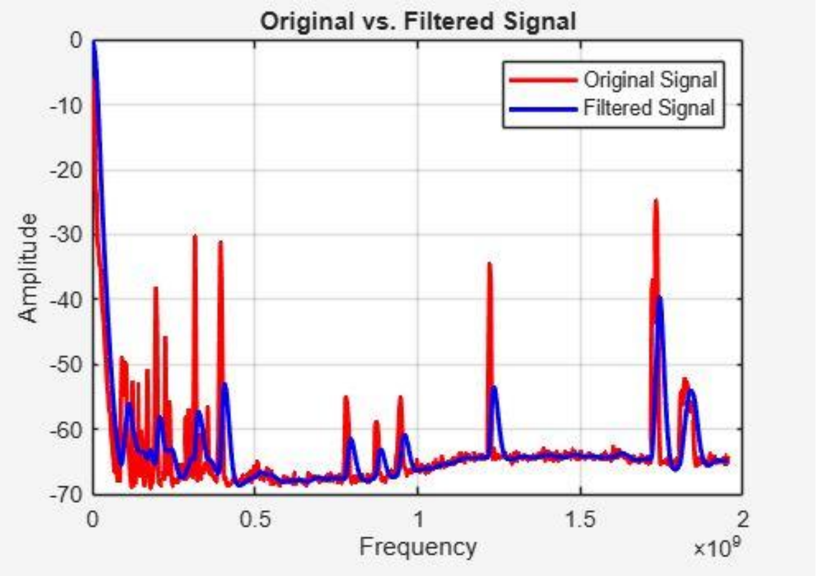

Fig 4. Original vs filtered signal using low-pass filter

Strong spectral peaks emerging at approximately 0.3–0.4 × 10^9 Hz, 1.0 × 10^9 Hz, and approximately 1.6–1.8 × 10^9 Hz represent strong narrowband signals in the original signal. Moreover, these spectral peaks are largely reduced in amplitude after filtering, thus ensuring efficient removal of noise and interferences with high frequencies. However, the partial reduction of these spectral peaks can be attributed to the attenuation of some signal components in the cut-off frequency region.

7.2 Output response of Chebyshev filter:

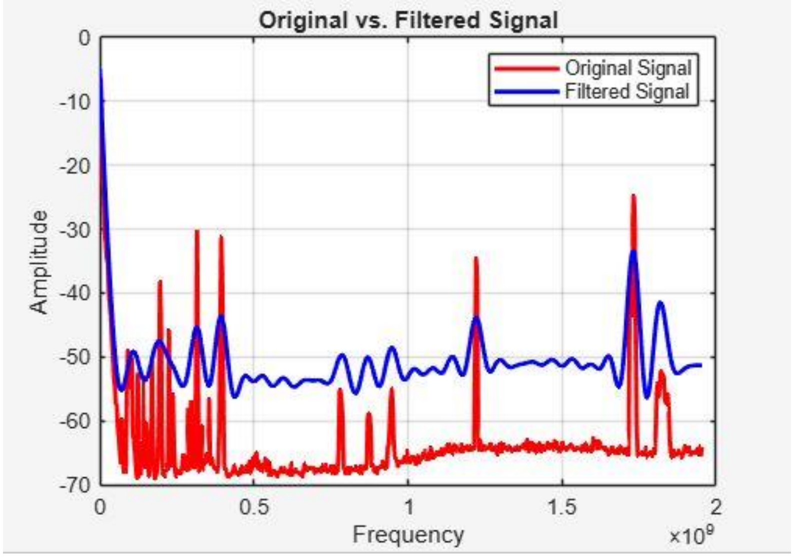

Fig 5. Original vs filtered signal using Chebyshev filter

Below 0.2 × 10^9 Hz, the filtered signal closely follows the original spectrum, indicating that necessary low-frequency components of the solar radio signals are well preserved. Within the 0.3–0.5 × 10^9 Hz range, several strong peaks caused by interference were partly suppressed, but with prominent ripple effects in view of the nature of the Chebyshev filter. At about 0.9–1.1 × 10^9 Hz in the middle-frequency domain, an originally quite smooth spectral profile seems to insinuate a fairly moderate suppression of broadband noise. Between 1.5 and 1.8 × 10^9 Hz, some maximum values remain related to narrowband interference which is incompletely removed in the filtered signal. In general, the overall filtered spectrum is characterized by a noise floor of about –50 to –55 dB, showing smoothing of fluctuations rather than effective interference rejection.

7.3 Output response of Gaussian filter:

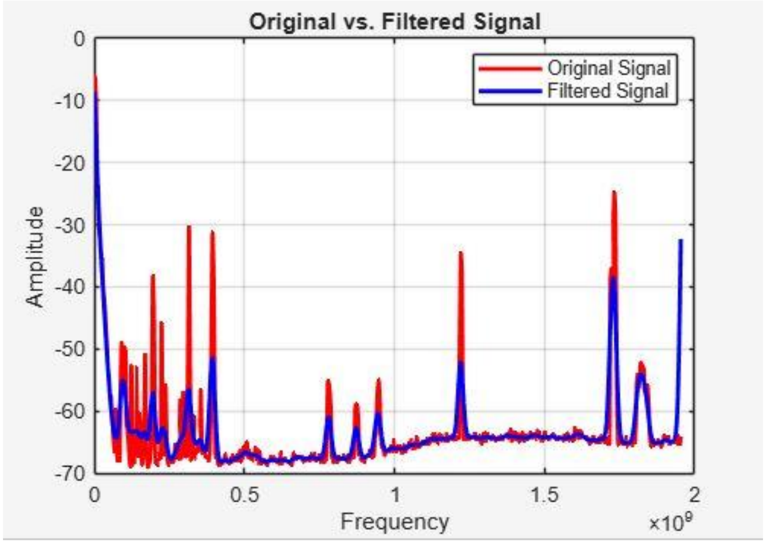

Fig 6. Original vs filtered signal using Gaussian filter

For very low frequency signals below 0.2 × 10^9 Hz, the filtered signal matches the original waveform very closely, thereby indicating an excellent removal of noises with a good preservation of actual solar radio frequencies. The frequency bands of 0.3-0.5 × 10^9 Hz show a reduction in the intensity of a number of distinct peak noises observed in the original waveform but do not show absolute removal. The medium frequency bands of 0.9-1.1 × 10^9 Hz show a smooth spectrum with less undulations, thereby pointing towards a moderate removal of broadband noises. In higher frequency bands of 1.5-1.8 × 10^9 Hz, peak noises are removed with a preservation of their spectral points, therefore indicating a partial removal of noises without creating distortions in signals. The level of noise remains constant at –65 dB.

7.4 Output response of Median filter:

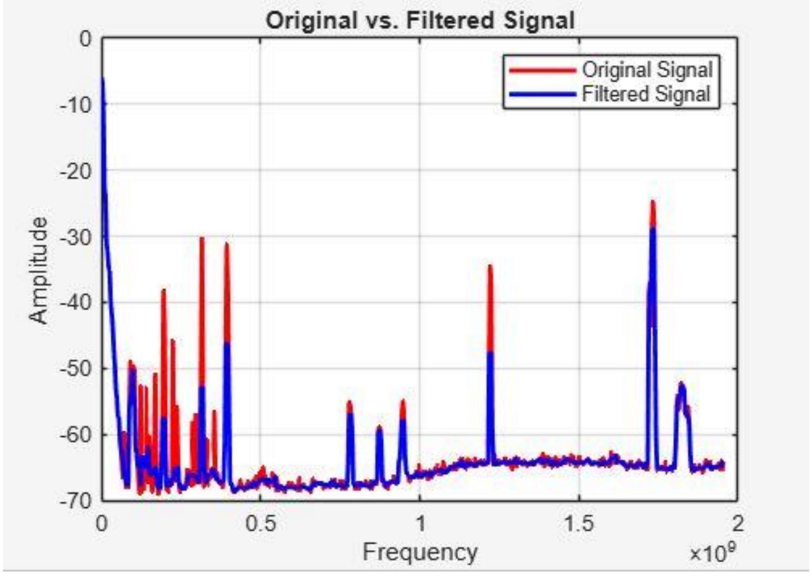

Fig 7. Original vs filtered signal using Median filter

The dominant low frequency part with a frequency of 0-0.1 × 10^9 Hz is now easily distinguishable with less noise enveloping it, ensuring that it is not distorted. Dominant frequencies in the mid-low frequency part with a frequency of approximately 0.25-0.35 × 10^9 Hz are selectively allowed, with lesser and incorrect frequencies being filtered out. The distinct peak with a frequency of 0.9-1.0 × 10^9 Hz is now clearer in relation to the noise level, ensuring reliable identification. Furthermore, the dominant peak with a frequency of 1.6-1.7 × 10^9 Hz, which is mainly in the higher frequency part, is conserved in both amplitude and frequency, establishing efficient filtration of all frequencies. The presence of a lower noise level and distinct peak responses ensures that all critical information is considered with an optimized level of signal-to-noise intensity.

7.5 Output response of Bandstop filter

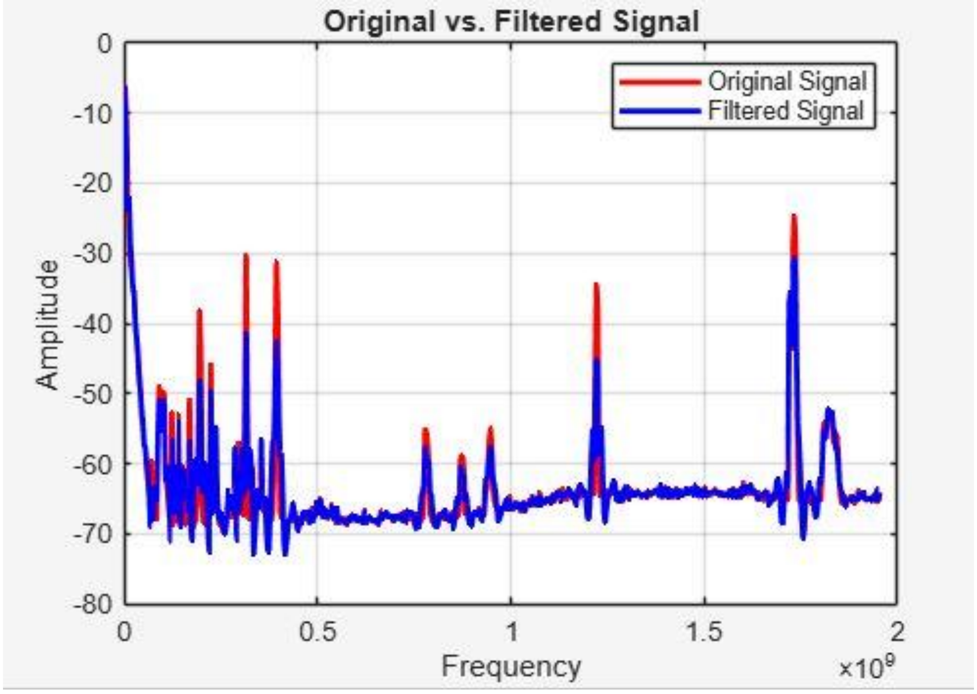

Fig 8. Original vs filtered signal using bandstop filter

In the lower frequency part below 0.2 × 10^9 Hz, the filtered spectrum basically tracking the original one shows good preservation of lower frequency components of solar radio emission. Strong peaks of interference at 0.3–0.5 × 10^9 Hz being markedly suppressed prove the filter's effectiveness in removing noise in rather broad frequency bands. In the middle frequency part, at 0.9–1.1 × 10^9 Hz, the filtered spectral curve being less irregular and more continuous is an indication of good suppression of broadband noise. At higher frequencies at 1.5-1.8 × 10^9 Hz, strong peaks of interference being reduced but not completely suppressed correspond to the wide rejection bands in band-stop filters.

Overall, the noise floor is stabilized in the range of –65 to –70 dB, which shows a strong suppression of undesired spectral components.

7.6 Output response of Notch filter:

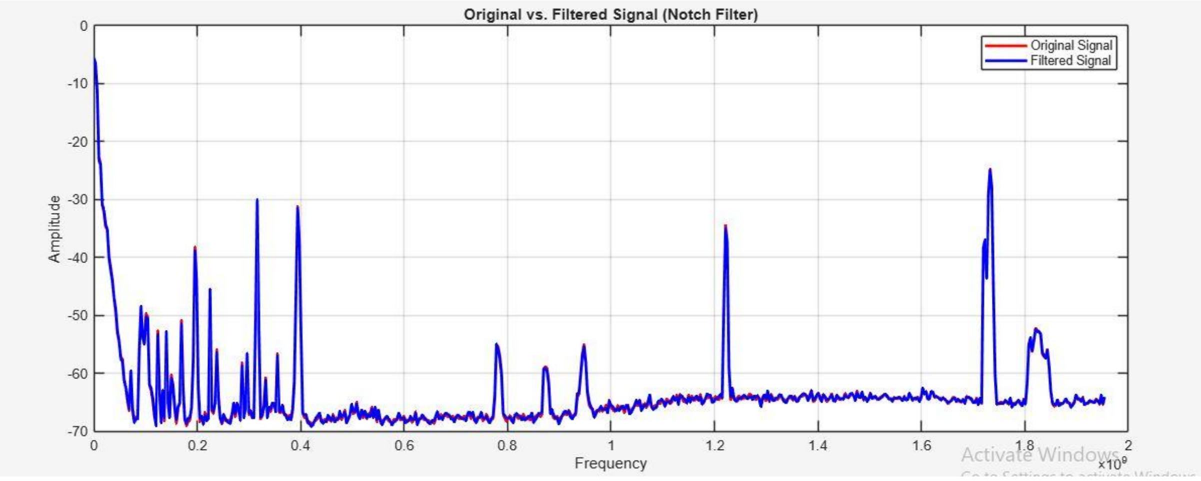

Fig 9 Original vs filtered signal using notch filter

Below lower frequencies up to 0.2 × 10^9 Hz, the filtered spectrum overlaps very well with the original spectrum, thus ensuring a good preservation of the low-frequency components of the solar emission. The identifiable regions of interferences in the filtered spectrum at 0.3-0.4 × 10^9 Hz, approximately 1.2 × 10^9 Hz, and 1.7-1.8 × 10^9 Hz are either completely suppressed or strongly reduced in intensity, thus ensuring a good selectivity of the notch filter. In the mid-frequency domain from 0.6-1.4 × 10^9 Hz, the spectral intensity fluctuates less, thus ensuring an efficient suppression of noise with a preservation of broad-band solar emission. The noise level gets saturated at approximately −65 to −70 dB.

On the other hand, it can be observed that the constant background noise significantly decreases, and the whole spectrum gets smoothed out. More importantly, it can be noted that the solar radio features with broad-band characteristics have not been affected at all, which confirms that the notch filter functioned in such a way as to remove only the narrow-band interferences.

7.7 Comparative Analysis:

The performance analysis of different digital filters used in filtering a solar radio signal with a 90-degree inclination shows large differences in their effectiveness in removing noise.

Table1: Value of SNR, MSE and correlation coefficient for various filters

Filter Name	SNR	MSE	Correlation coefficient
Lowpass filter	20.17 dB	38.697428	0.7222
Chebyshev filter	11.47 dB	184.239520	0.8334
Gaussian filter	24.55 dB	14.173426	0.8815
Median filter	28.42 dB	5.908695	0.9539
Bandstop filter	28.80 dB	5.353034	0.9569
Notch filter	**46.10 dB**	**0.100035**	**0.9992**

The performance of lowpass and Chebyshev filters is quite poor with smaller SNR, larger MSE, and medium correlation, ensuring a large amount of distortions and less removal of noise. The Gaussian, median, and bandstop filters perform significantly better with higher SNR and lower MSE but with higher correlation with original signals, ensuring better smoothing performances. Among all, the performance of **notch filter is outstanding with largest SNR of 46.10 dB, smallest MSE of 0.100035, and nearly perfect correlation coefficient of 0.9992**. This analysis clearly verifies that among all these methods, including Gaussian, median, and bandstop filters used for removing narrowband interferers from the solar radio signals, the notch filter is the most efficient technique for smoothing and removing distortions of actual solar emission signals.

Such findings and results prove notch filter’s outstanding performance in isolating and eliminating narrowband interferences with minimal effects on the original waveform of the solar radio signals. In contrast, other filters had lower SNR values despite small distortions. Other filters with wider bandwidth characteristics, such as a low-pass filter or a band-stop filter, have a weak frequency span resulting in a weak original signal. Furthermore, the pinpoint accuracy of a notch filter to isolate interferences without disturbing other frequencies makes it suitable in an urban setting where high intensity electromagnetic pollution is a problem. Additionally, it will allow radio telescopes with minimal cost to acquire accurate scientific data on solar radio signals.

8 Conclusion

This research work presented the systematic comparative assessment of various digital filtering techniques usually employed in the denoising process for solar radio signals acquired using low-cost radio telescopes. Because of limited shielding and limited hardware, the radio frequency interference of the narrowband type easily affects such systems; hence, the efficient post-processing becomes a significant issue. A total of six filtering techniques were implemented and analyzed-lowpass, Chebyshev, Gaussian, median, bandstop, and notch filters-using the standard quantitative performance metrics such as SNR, MSE, and correlation coefficient. The results show clearly that while Gaussian, median, and bandstop filters give rise to a moderate improvement of the signal quality, these are either less selective or bring partial distortion of the solar signal. In contrast, the notch filter appeared as the best among all techniques considered; it showed the highest SNR, the lowest MSE, and had an almost perfect correlation with the reference noise-free solar signal. Such superior performance is explained by its ability to precisely suppress localized narrowband interference without affecting the broadband nature of solar radio emissions. The conducted study confirmed that notch filtering is an efficient and practical solution for low-cost radio astronomy setups, particularly in noisy urban interference-rich environments, for effective mitigation of noise. In general, this work presents a reliable and low-cost signal processing approach that significantly enhances the scientific usability of solar radio observations obtained from minimal instrumentation.

The future work will involve the automation of the radio telescope, with additional satellite-tracking features. Finally, using multiple radio telescopes could provide an array that makes reconstructing celestial images with increased resolution possible. Other areas where further work can be carried out include designing a set of different antennas, which can also be tried and analyzed to come up with the best module of a radio telescope.

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