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A STUDY ON THE INFLUENCE OF WINDOW FUNCTIONS IN THE SPECTRUM OF THE RADAR SIGNAL

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Abstract: This paper discusses the influence of window functions on the spectrum of radar signals. Signal processing was done to translate the signal from the time domain to range/distance estimation and optimization of defining the target using windowing. The window functions used are Hamming, Hanning and Blackman. A complex noise-affected signal consisting of two components (a higher amplitude component, and a smaller amplitude component), is considered for analysis. In other words, one of the targets is stronger and the second target is forty times weaker. The cases in which the targets are close to each other and in which they are far apart in terms of the Doppler frequency are simulated for each window. The results show that the Hamming window provides the most accurate spectral estimation for closely spaced targets, while the Hanning window offers superior performance when the targets are well separated, emphasizing the importance of both sidelobe level and decay characteristics in radar spectral analysis.

Keywords: *Radar; Spectral leakage; Power Spectral Density; FFT; Windowing; Hamming Window; Hanning Window; Blackman Window.*

I. INTRODUCTION

Modern radar systems play a crucial role in various fields such as automotive safety, aviation, defense and autonomous navigation. These systems operate by transmitting electromagnetic signals, receiving reflections from surrounding objects and extracting key information such as distance, speed, and direction [1].

To analyze radar signals effectively, it is often necessary to observe how their energy is distributed across different frequencies. When examining a signal over a limited time duration, as is the case with real-world radar measurements, artificial boundaries are introduced at the start and end of the data segment. These abrupt edges can lead to distortions in the spectral content, affecting the accuracy of frequency-related information.

A common result of this effect is spectral leakage, where the energy of a distinct frequency component spreads into adjacent frequency regions. This reduces the sharpness and reliability of the spectral estimate. To mitigate such effects, window functions are applied to the signal prior to spectral analysis. These functions modify the signal's shape by gradually tapering its edges, thereby minimizing discontinuities and improving control over the distribution of energy across the frequency range.

In radar applications, the proper selection and use of a window function are essential, as they directly influence the system's ability to detect and separate frequency components accurately. The importance of window functions in optimizing performance in complex urban environments is also highlighted in the paper [2] which provides an overview of the architecture and signal processing in automotive radar systems. Additionally, in [3], modern signal processing techniques are used in automotive radar, including window functions, which play a significant role in improving frequency resolution and reducing interference. The study [4] proposes a partially adaptive MIMO beamforming technique to mitigate interference caused by multiple reflections, using window functions to improve the signal-to-noise ratio and reduce the effects of spectral leakage. In [5], window functions (Hann, Hamming, Blackman-Harris, Tukey) are compared in the processing of FMCW radar signals, highlighting their impact on detection performance and frequency resolution. The paper [6] presents a detailed analysis of signal processing window functions and their role in reducing spectral leakage in Discrete Fourier Transform (DFT) analysis, particularly in Global Navigation Satellite Systems (GNSS). The comparison contrasts traditional methods that rely on rectangular windows with approaches employing optimized window functions such as Blackman, Kaiser, and Hanning. The study emphasizes the critical role of selecting a suitable window function, depending on the application context and the signal-to-noise ratio (SNR) available. The study [7] demonstrates that spectral leakage, resulting from analyzing signals over finite time windows, can significantly degrade the accuracy of parameter estimation in radar systems by spreading energy into unwanted sidelobes. The study highlights that the application of window functions such as Hanning, Hamming, or Blackman is crucial for mitigating these effects and achieving a cleaner and more stable spectral representation. The paper [8] highlights the importance of window function design, such as Hanning and Blackman, for reliable signal detection under jamming conditions. Thus, the correct use of window functions plays a crucial role in improving the overall performance of modern radar systems, being fundamental for automotive applications and other high precision.

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This research highlights the importance of window functions in improving the spectral resolution of radar signals, with emphasis on the Hamming, Hanning and Blackman windows. We show two scenarios, with two targets that are close respectively far apart from each other. One target is weak and the other one is strong. We show the best window function to detect the weak target in each case. The paper is structured as follows: window functions are shown in Section 2, their power spectral density is given in Section 3 with simulation results in Section 4. Conclusions are drawn in the last section of the paper.

II. WINDOW FUNCTIONS

Window functions play a key role in radar signal processing, especially in technologies that use the Fourier transform (FFT) for signal analysis. They are used to improve measurement accuracy and reduce unwanted effects during signal processing. There are distinct types of window functions that can be applied depending on the signal. The simplest window function is rectangular window or Dirichlet window and can be seen as a rectangular window that applies a constant coefficient throughout the window. The Dirichlet window is easy to implement and has a low complexity, but it produces a spectrum with large side lobes and may lead to aliasing.

$$w[n] = 1 \quad for\ 0 \le n < N \tag{1}$$

In the same category of simple window functions is the Barlett window, named triangular window, used to reduce spectral leakage. The triangular window`s performance is not as remarkable as other more advanced windows (such as Hamming windows).

$$w[n] = 1 - \left|\frac{2n}{N-1} - 1\right| \quad for\ 0 \le n < N \tag{2}$$

The Hamming family is defined as:

$$\mathrm{w_H[n]} = \begin{cases} \alpha - (1-\alpha)\cos\left(\frac{2\pi}{\mathrm{N-1}}\right), & \text{for } 0 \le \mathrm{n} \le \mathrm{N}-1 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

If α = 0.54, the window is called the Hamming window, while if α = 0.5, it is called the Hanning window. The Hanning window is commonly used because of its ability to reduce spectral leakage and improve the separation of signals in the frequency domain, but it has a wide main lobe, which may reduce frequency resolution.

On the other hand, the Hamming window has a better side lobe reduction. It is useful in signal processing applications because it offers a good compromise between frequency resolution and spectral leakage.

The Tukey Window, known as "Beta" window, is a combination of a rectangular window with a Hanning window. The flexibility of controlling the transition between windows based on application needs using a parameter α is the main advantage of this window.

$$\begin{cases} w[n] = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi n}{\alpha N}\right)\right], & for\ 0 \le n < \frac{\alpha N}{2} \\ w[n] = 1, & for\ \frac{\alpha N}{2} \le n \le \frac{N}{2} \\ w[N-n] = w[n], & for\ 0 \le n \le \frac{N}{2} \end{cases} \tag{4}$$

The Blackman window has excellent leakage suppression. Compared to the Hamming window and Hanning window, the Blackman window further reduces the spectral leakage.

$$\mathrm{w_{BL}[n]} = 0.42 - 0.5\cos\left(\frac{2\pi n}{\mathrm{N-1}}\right) + 0.08cos\left(\frac{4\pi n}{\mathrm{N-1}}\right) \tag{5}$$

$$\text{for } 0 \le \mathrm{n} \le \mathrm{N} - 1$$

Enhanced Blackman variant with even lower side lobes is Blackman-Harris window. Even though this window has a high computation complexity, it is preferred for its minimal spectral leakage.

$$\mathrm{w[n]} = \mathrm{a_0} - \mathrm{a_1}\cos\left(\frac{2\pi n}{\mathrm{N-1}}\right) + \mathrm{a_2}\cos\left(\frac{4\pi n}{\mathrm{N-1}}\right) - \mathrm{a_3}\cos\left(\frac{6\pi n}{\mathrm{N-1}}\right) \tag{6}$$

$\mathrm{a_0} = 0.35875$, $\mathrm{a_1} = 0.48829$, $\mathrm{a_2} = 0.14128$, $\mathrm{a_3}$=0.0116.

The choice of a window function for signal processing depends on the characteristics of the signal and the specific application. The rectangular window is simple and effective for signals that do not require precise frequency separation.

The Hanning and Hamming windows are ideal for most general applications, offering a good compromise between resolution and reducing spectral leakage. The Blackman window, like the Blackman-Harris window, significantly reduces spectral leakage and is particularly useful for improving frequency resolution when signals are close together in frequency. The Blackman-Harris window offers even further reduction of side lobes but is more complex to compute.

The Tukey window is useful when you need to control the transition between rectangular and Hanning windows, providing flexibility in how the window is shaped based on application needs.

One of the most critical parameters when evaluating a window's performance is the Peak Side Lobe Level (PSLL), which measures the amplitude of the highest sidelobe relative to the main lobe. A high PSLL can lead to energy from strong frequency components leaking into adjacent bins, which may mask weaker signals, particularly problematic in radar systems where low-SNR targets must be accurately detected.

Windows such as Blackman or Blackman-Harris are preferred in applications where sidelobe suppression is essential, as they exhibit significantly lower PSLL compared to simpler windows like rectangular or Hanning. Although these advanced windows may sacrifice some frequency resolution due to a wider main lobe, the reduced sidelobe level ensures more reliable target detection and cleaner spectral representation.

Thus, PSLL becomes a decisive criterion in window selection, especially in high-precision radar, communication, or vibration analysis systems. Lowering the PSLL effectively minimizes spectral leakage, enhancing the interpretability and reliability of the Power Spectral Density (PSD) estimation. Peak Side Lobe Level compares the size of the highest sidelobe to the size of the main lobe. PSLL is given by:

$$\mathrm{PSLL} = 20\log_{10}\left(\frac{maximum\ \text{sidelobe value}}{\text{main lobe value}}\right) \tag{7}$$

Choosing the right window is crucial for optimizing the performance of radar systems and other high-precision signal processing applications.

III. POWER SPECTRAL DENSITY

In discrete signal analysis, estimating the Power Spectral Density (PSD) is essential for understanding how a signal's energy is distributed across frequencies. However, applying the Fourier Transform to a finite segment of the signal can introduce distortions that affect the accuracy of the results.

Spectral leakage is the most common issue that causes the energy of a frequency component to spread around its true value, affecting the clarity of the spectrum. This phenomenon primarily occurs due to the abrupt truncation of the signal, which is equivalent to multiplying it by a rectangular window. In the frequency domain, this corresponds to a convolution with a sinc function, resulting in high sidelobes and energy spreading into adjacent frequencies – see Figure 1.

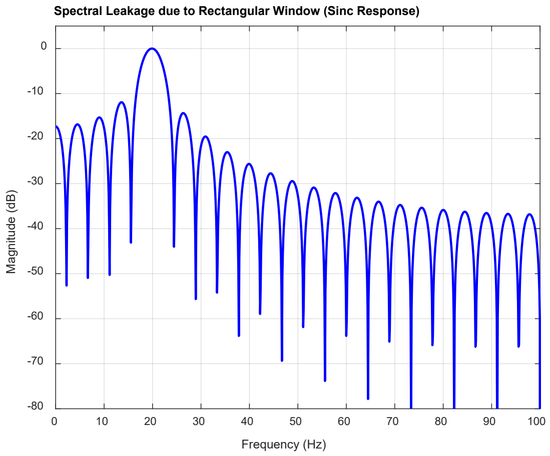

Figure 1. Spectral leakage due to the abrupt truncation of the signal.

To reduce the unwanted effects that can occur during spectral analysis, window functions are applied to the signal before transforming it into the frequency domain. Each type of window offers different balances between frequency resolution (related to the width of the main lobe) and the suppression of spectral leakage (influenced by the sidelobe levels).

Choosing the appropriate window function depends on the specific objectives of the analysis. When the goal is to detect weak signals in the presence of much stronger components, windows with low sidelobe levels are more effective, as they help minimize spectral leakage.

On the other hand, when the focus is on separating frequencies that are remarkably close together, windows with narrower main lobes are preferred because they offer better resolution.

Window functions are essential in spectral analysis. They improve the quality of the Power Spectral Density (PSD) estimation by reducing leakage and allowing for a more accurate and readable frequency representation. Their correct use is especially important in radar signal processing, as well as in fields like telecommunications, mechanical diagnostics, and any application that requires detailed frequency analysis.

Figure 2 shows the Hamming window function, Figure 3 shows the Hanning window function and Figure 4 shows the Blackman window function, all in discrete time.

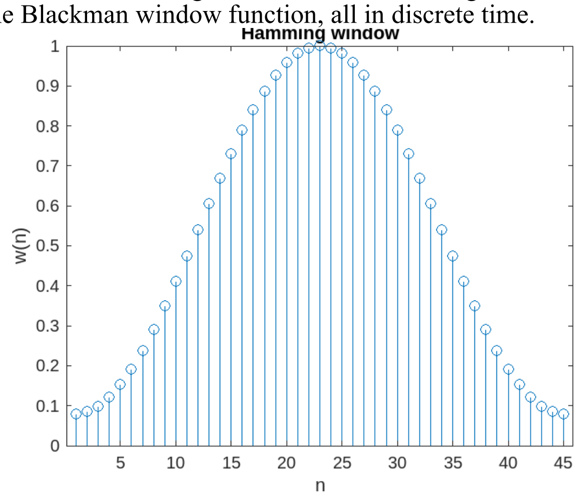

Figure 2. Hamming window.

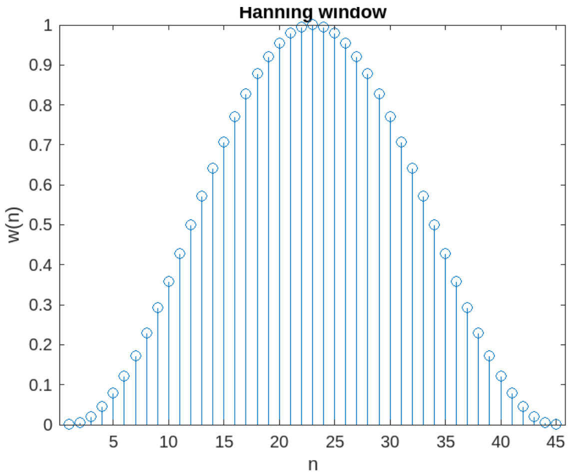

Figure 3. Hanning window.

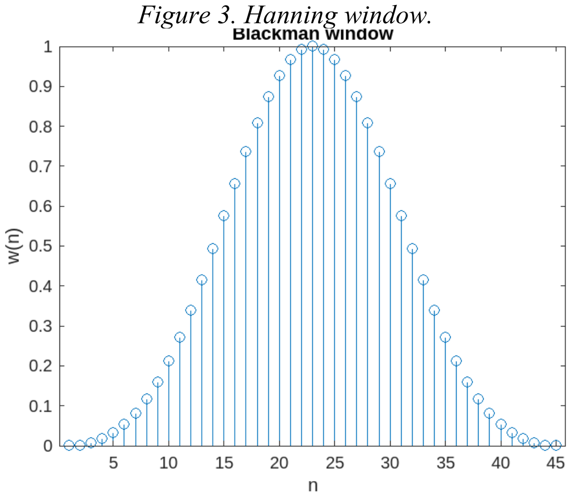

Figure 4. Blackman window

Figure 5 illustrates the spectra for different windows studied, with a length of N=45, including the rectangular window, for comparison.

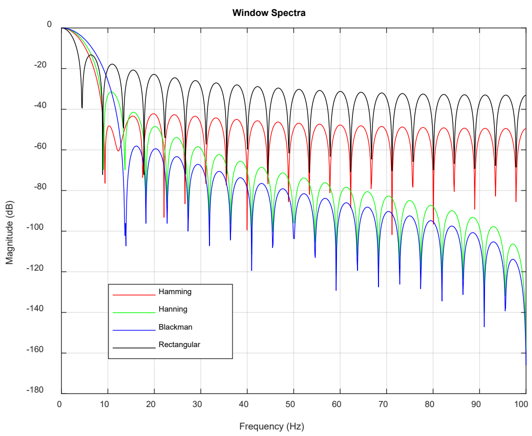

Figure 5. Spectra for different windows including the rectangular window, for window length of N=45.

For the windows considered, we estimate the PSLL values. These results are shown in Table 1, noting that the Hamming window has the lowest PSLL value, followed by Hanning then Blackman. The worst value of PSLL is the one for the rectangular window. The -13.25 dB side lobes are not acceptable in radar. Usually, several targets are observed, some have low power levels (with variations of tens of decibels). Consider the Doppler spectrum of a signal that contains echoes from 2 targets. If the discrete time Fourier transform DTFT peak of a low power target is equal to or smaller than the side lobes of the higher power target, the side lobes of the stronger target with mass the DTFT of the weaker target and only a stronger target will be observed.

Table 1. PSLL values

Window	PSLL (dB)
Hamming	-42.21 dB
Hanning	-31.47 dB
Blackman	-24.37 dB
Rectangular	-13.25 dB

IV. MATLAB-BASED SIMULATIONS

Applying a window in the time domain (which consists of multiplying the signal by a window function) results in a convolution effect in the frequency domain. The type of window used determines how the spectral content is smoothed. This window smoothing effect reduces fluctuations in the power spectral density (PSD) estimate and leads to a more stable and improved representation of the signal's frequency content.

The signal used in the simulations is complex and has two complex sinusoids: one with higher amplitude ($A_1 = 2$) and one with lower amplitude ($A_2 = 0.05$), corresponding to two radar targets with different Doppler frequencies. In other words, one target is strong, while the second is forty times weaker. In both scenarios, the window length $N = 45$ and the sampling frequency $f_s = 200$ Hz were consistently applied for all window types (Hamming, Hanning, and Blackman). These parameters provide a balance between frequency resolution and temporal localization, ensuring clear spectral separation while maintaining comparable conditions across the two scenarios.

We will consider scenarios when the targets are close or apart from each other, in terms of Doppler frequency, as well as the case of signal without noise, and signal affected by noise. For example, the first target is set at f_1=25 Hz and the second target is set at f_2=40 Hz for close targets scenario 1, and 80 Hz for the scenario 2 with targets that are far away from each other. The added noise is complex valued with a standard deviation of σ=0.15. This signal remains the same across all simulations to ensure consistent analysis. The study evaluates the influence of the Hamming, Hanning, and Blackman window functions on radar signal's spectral representation.

Table 2. SNR values for each target

Target	Amplitude	SNR (dB)
1	$A_1 = 2$	19.48 dB
2	$A_2 = 0.05$	-12.54 dB

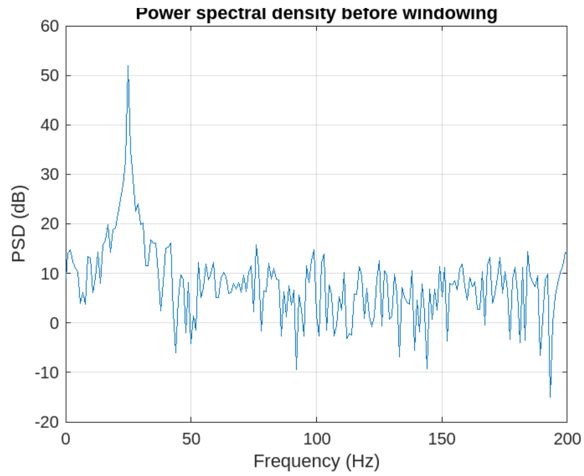

Figure 6a. Power spectral density of the signal affected by noise before the application of the window – scenario 1 (close targets).

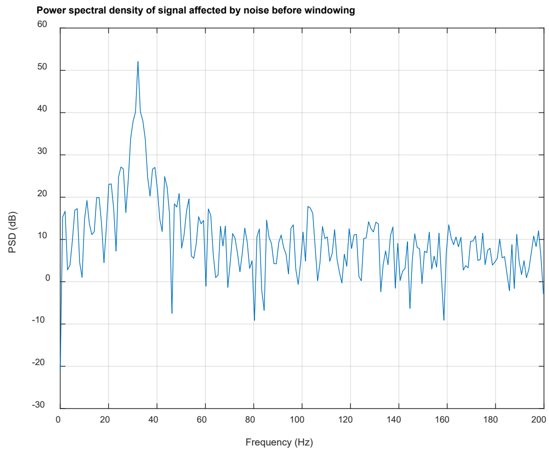

Figure 6b. Power spectral density of the signal affected by noise before the application of the window – scenario 2 (far away targets).

Figures 6a and 6b present the power spectral density (PSD) of the signal affected by noise, before the application of any window to function – for scenario 1 (close targets) and scenario 2 (far away targets), respectively. In this unprocessed form, only the target associated with a high signal-to-noise ratio (SNR) is detectable, while the weaker component remains obscured due to spectral leakage and noise interference.

I. Scenario 1: Targets are close to each other.

The first scenario considered aims to see the influence of the window functions in the radar signal spectrum when the Doppler frequencies of the two targets are close (this can correspond for example to close distance or close velocities).

1. Hamming Window

Figure 7 presents the power spectral density (PSD) of the signal after the application of the Hamming window. The presence of noise remains visible. Prior to windowing, only the target with a high signal-to-noise ratio (SNR) was distinguishable. While the Hamming window significantly smooths the periodogram, it does not allow for the detection of the weaker target.

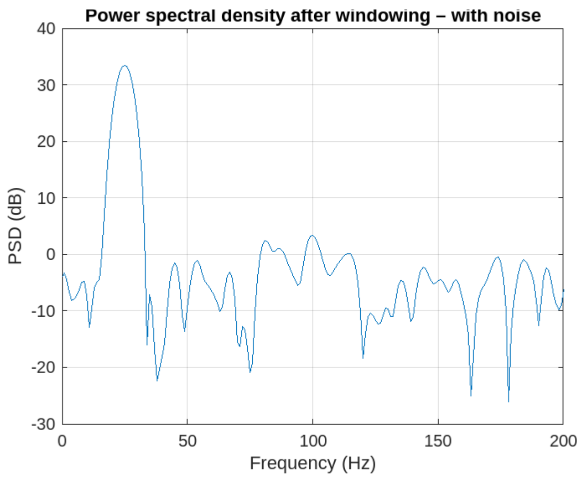

Figure 7. Power spectral density after applying the Hamming window.

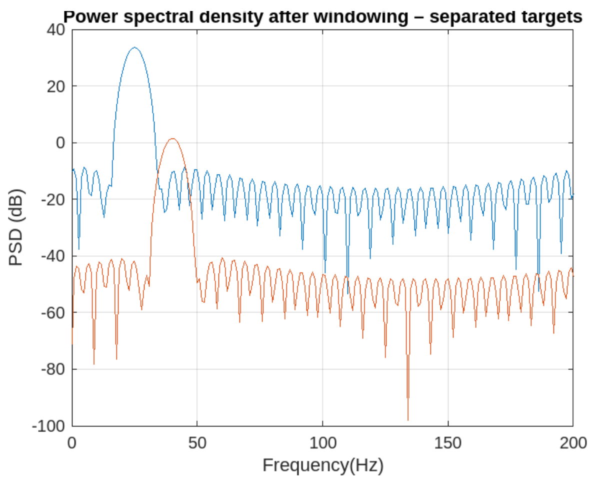

Figure 8. Power spectral density of targets after application of the Hamming window - separate targets

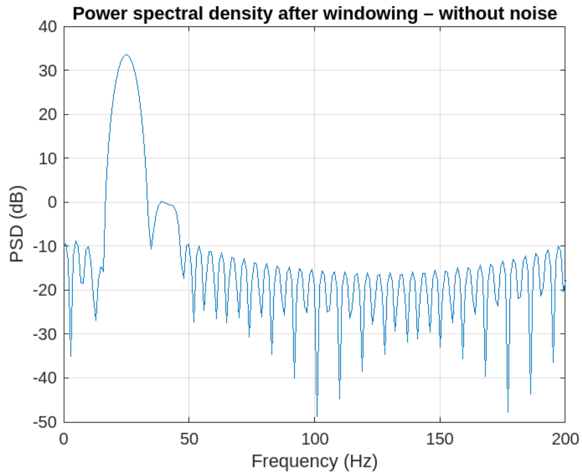

Figure 9. Power spectral density of a signal without noise after application of the Hamming window

In Figure 8, the PSD of the strong target is shown in blue, and that of the weak target is shown in orange — both after applying the Hamming window. It can be observed that the spectral components of the two targets overlap, making it difficult to separate them clearly.

Figure 9 displays the PSD of the signal without noise, after applying the Hamming window. In this case, both the strong and the weak targets are clearly identifiable, confirming that noise masking plays a significant role in target visibility.

2. Hanning Window

Figure 10 illustrates the PSD of the signal after applying the Hanning window. The presence of noise is still noticeable. Before the application of the window, only the target with a high signal-to-noise ratio (SNR) could be detected. Although the Hanning window smooths the periodogram, the weaker target remains difficult to identify.

Figure 11 shows, in blue, the PSD of the strong target after applying the Hanning window, and in orange, the PSD of the weaker target under the same conditions. The overlap between the two spectral components makes it challenging to distinguish the weaker target.

Figure 12 presents the PSD of the signal without noise, after the application of the Hanning window. In this case, both the strong and the weak targets are clearly visible, indicating that noise significantly affects the detectability of low-SNR targets, even after windowing.

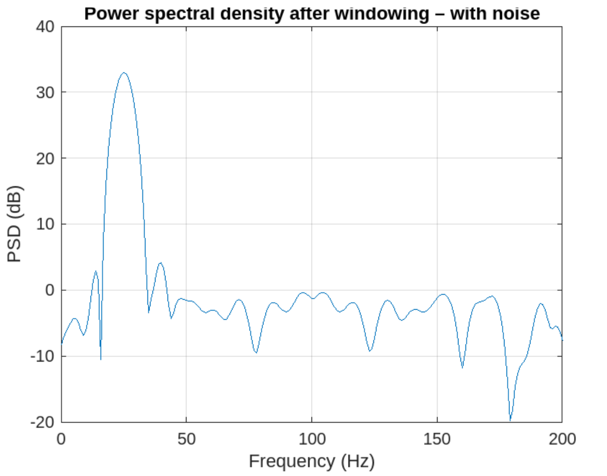

Figure 10. Power spectral density after applying the Hanning window.

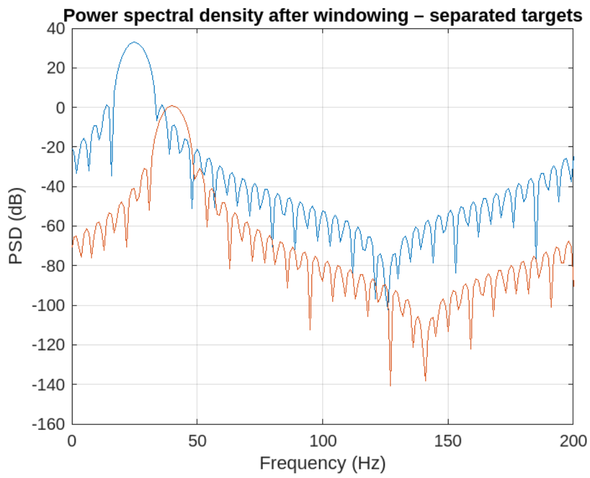

Figure 11. Power spectral density of targets after application of the Hanning window - separate targets

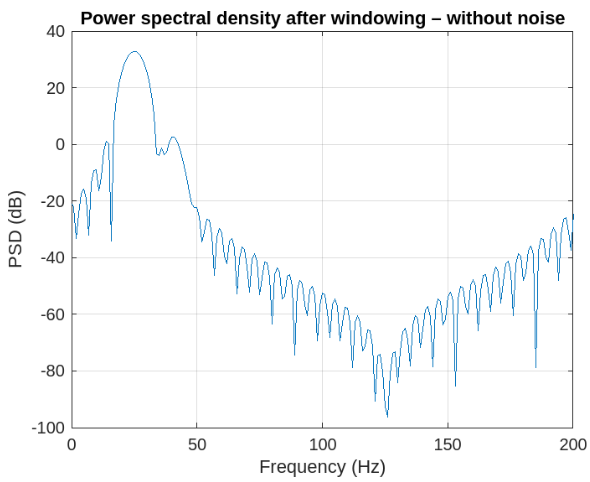

Figure 12. Power spectral density of a signal without noise after application of the Hanning window

3. Blackman Window

Figure 13 presents the power spectral density (PSD) of the signal after the application of the Blackman window. The presence of noise remains noticeable. Prior to applying the window, only the target with high signal-to-noise ratio (SNR) was detectable. While the Blackman window effectively smooths the periodogram, it does not allow for the identification of the weaker target under noisy conditions.

In Figure 14, the PSD of the strong target is shown in blue, and that of the weak target is shown in orange, both after applying the Blackman window. It can be observed that the weaker target is masked by the main lobe and partially by the side lobes of the strong target, making it difficult to isolate.

Figure 15 displays the PSD of the signal without noise, after applying the Blackman window. In this noise-free scenario, the strong target is clearly visible, and the weak target also becomes identifiable, indicating that the Blackman window enhances target separation when noise is not present.

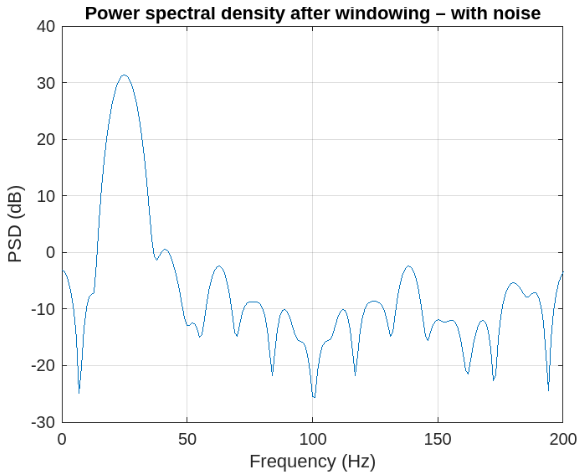

Figure 13. Power spectral density after applying the Blackman window.

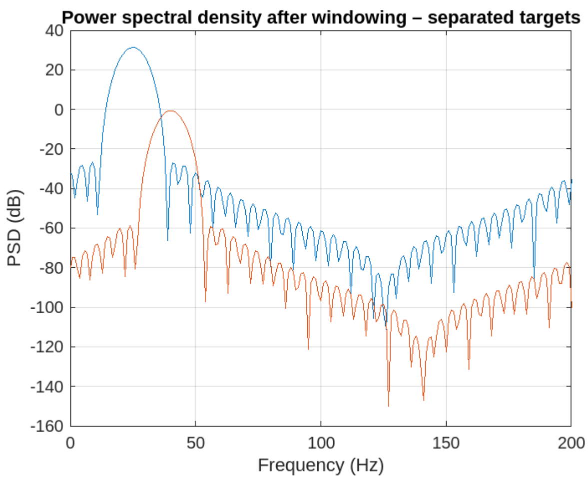

Figure 14. Power spectral density of targets after application of the Blackman window - separate targets

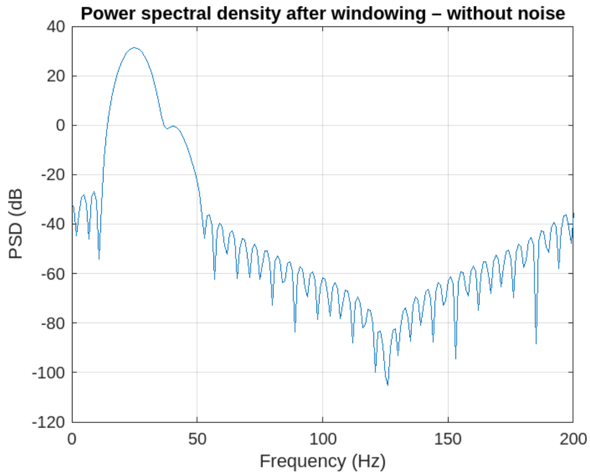

Figure 15. Power spectral density of a signal without noise after application of the Blackman window

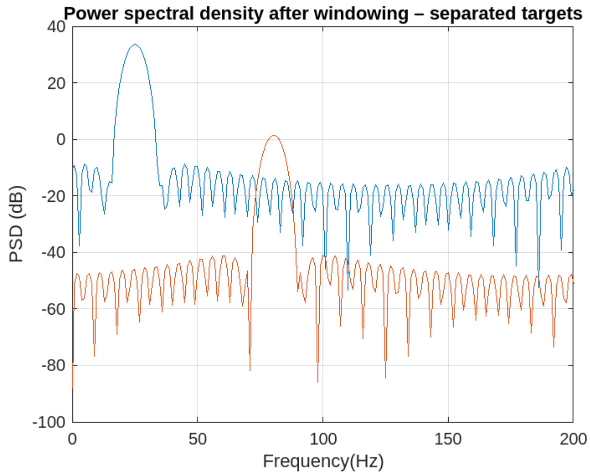

Figure 17. Power spectral density of targets after application of the Hamming window - separate targets

II. Scenario 2: Targets are far away from each other.

This second scenario aims to see the influence the window functions in the radar signal spectrum when the Doppler frequencies of the two targets are far away (this can correspond for example to targets far in distances or velocities).

1. Hamming Window

Figure 16 illustrates the power spectral density (PSD) of the signal after applying the Hamming window. Noise is still present in this case, and only the strong target can be clearly identified.

Figure 17 shows the PSD of the strong target in blue and the PSD of the weak target in orange, both after the application of the Hamming window. In this scenario, the two targets are no longer overlapping, and both components are distinguishable.

Figure 18 presents the PSD of the noise-free signal after applying the Hamming window. In this case, both targets can be accurately located, confirming improved visibility when noise is absent.

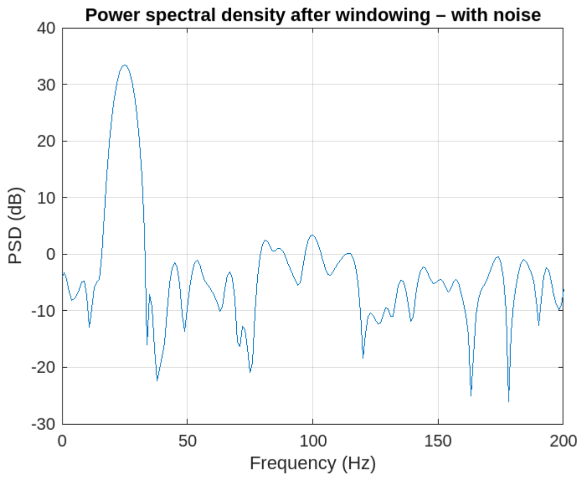

Figure 16. Power spectral density after applying the Hamming window.

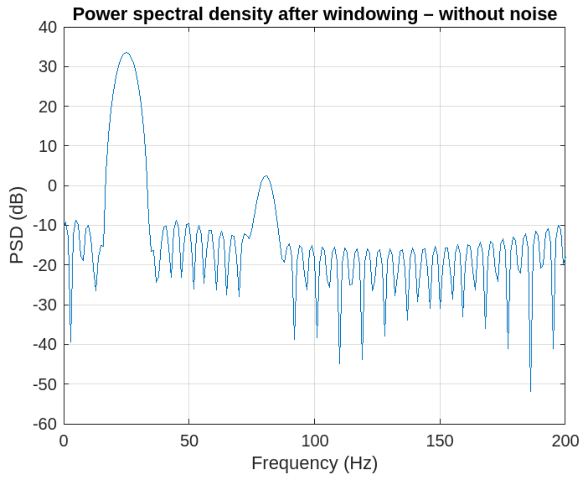

Figure 18. Power spectral density of a signal without noise after application of the Hamming window

2. Hanning Window

Figure 19 illustrates the power spectral density (PSD) of the signal after applying the Hanning window. The presence of noise remains visible. IN this case, both the strong and the weak targets can be identified.

Figure 20 shows the PSD of the strong target in blue and that of the weak target in orange, after applying the Hanning window. The weak target is no longer masked by the spectral components of the strong one, allowing both to be distinguished clearly.

Figure 21 presents the PSD of the signal without noise, after applying the Hanning window. In this case, both targets are easily identifiable, further confirming the window effectiveness in scenarios with well-separated Doppler frequencies.

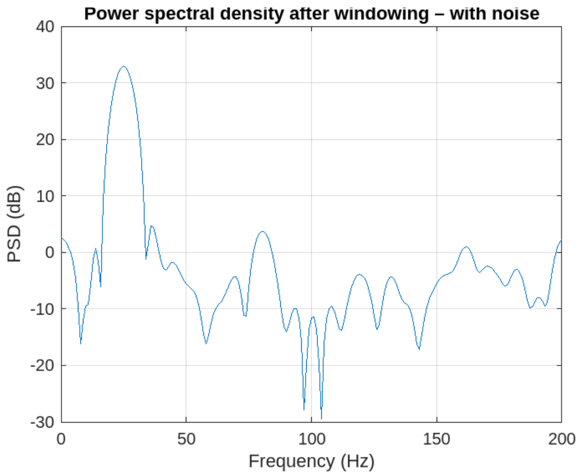

Figure 19. Power spectral density after applying the Hanning window.

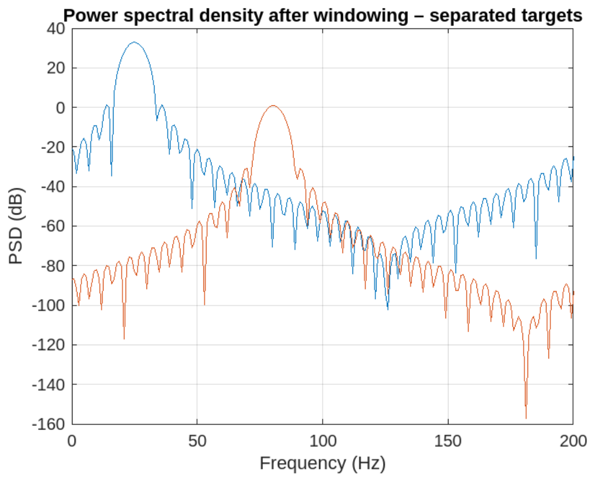

Figure 20. Power spectral density of targets after application of the Hanning window - separate targets

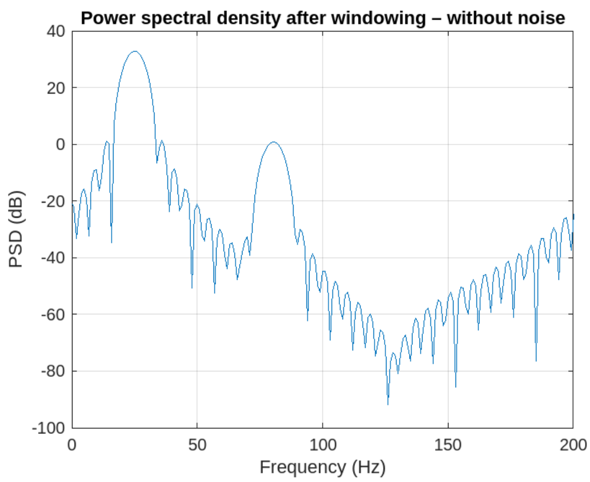

Figure 21. Power spectral density of a signal without noise after application of the Hanning window

3. Blackman Window

Figure 22 displays the power spectral density (PSD) of the signal after applying the Blackman window. Noise is still present in this case, and only a strong target can be identified. The weak target remains undetectable due to the influence of the strong target's side lobes.

Figure 23 shows the PSD of the strong target in blue and the PSD of the weak target in orange, both after the application of the Blackman window. In this scenario, the weak target is no longer obscured by the strong one, indicating improved target separation under these conditions.

Figure 24 presents the PSD of the noise-free signal after applying the Blackman window. In the absence of noise, both targets can be clearly identified, confirming the window's effectiveness when interference is minimal.

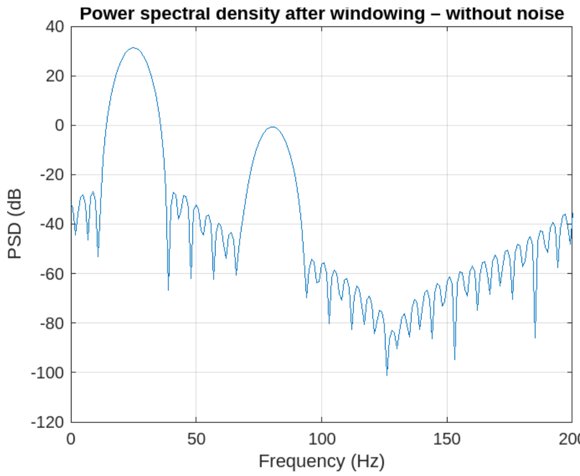

Figure 22. Power spectral density after applying the Blackman window.

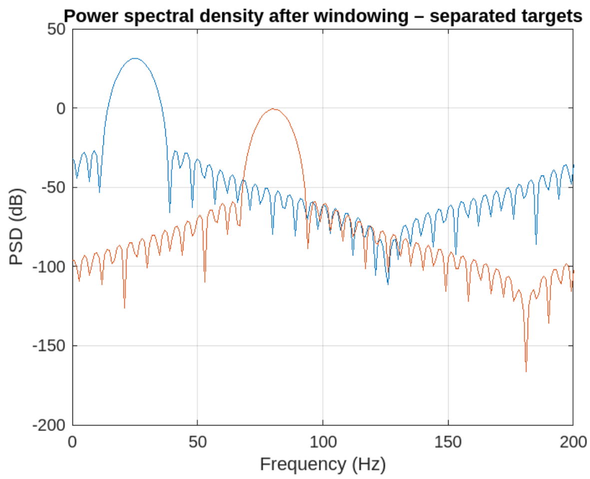

Figure 23. Power spectral density of targets after application of the Blackman window - separate targets

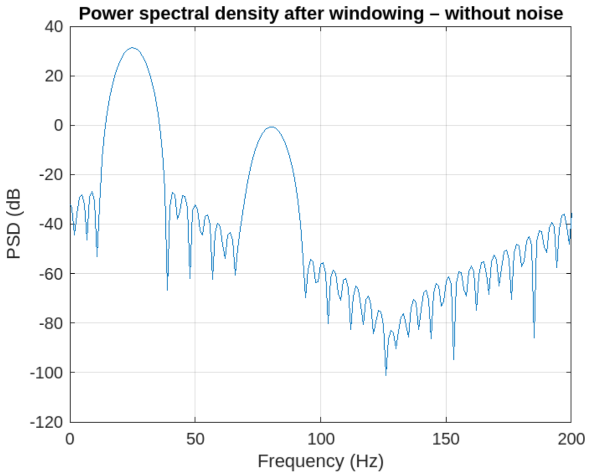

Figure 24. Power spectral density of a signal without noise after application of the Blackman window

V. CONCLUSION

This paper has investigated the impact of window functions on spectral analysis of complex radar signals. Windowing was applied as a method to reduce spectral leakage (a common issue when analyzing finite) duration signals in the frequency domain. The study was based on simulations involving a complex signal with two Doppler components, analyzed under two conditions: presence or absence of noise, and cases where the Doppler frequencies were either close together or well separated. The window functions evaluated were Hamming, Hanning, and Blackman.

In the first scenario, where the Doppler frequencies of the two targets are close, the Peak Side Lobe Level (PSLL) of the window function plays a significant role. A lower PSLL reduces the risk of the stronger target masking the weaker one through sidelobe interference. As shown in Table 1, the Hamming window, with the lowest PSLL (−42.21dB), offered the best suppression, contributing to clearer target separation compared to Hanning and Blackman windows, which exhibited higher sidelobe levels. When one target has much lower amplitude (low SNR), it can become masked by the side lobes of the stronger component. The analysis of the power spectral density (PSD) in the presence of noise revealed that only with the Blackman window the weaker target could not be identified (Figure 13). Although Hamming and Hanning windows share similar main lobe widths and allowed both targets to be detected, the Hamming window provided slightly better spectral clarity than Hanning. Even in noise-free conditions, the Hamming window yielded the most accurate spectral estimate among the three (Figures 9, 12, and 15).

In the second scenario, where the targets are spectrally well separated but differ in amplitude, the Hanning window demonstrated the best performance for identifying both targets in the presence of noise. While the Hamming and Blackman windows also offered smoothing, their side lobes decayed more slowly, making it more difficult to resolve the weaker component under noisy conditions. This behavior can also be explained considering the PSLL values. Although the Hamming window has the lowest PSLL, its sidelobes decay more gradually compared to those of the Hanning window. In the case of well-separated targets, the faster decay of Hanning's sidelobes, despite its slightly higher PSLL (−31.47dB), helps reduce long-range spectral interference. This allows the weaker target to be distinguished more effectively, especially in noisy conditions, highlighting that PSLL alone is not the only determining factor, sidelobe shape and decay rate are equally important in such scenarios.

In summary, window functions are essential tools for improving the quality of power spectral estimation. When targets are close in frequency, the Hamming window provides the most reliable results. When targets are well separated, the Hanning window achieved the best performance among the three analyzed window functions.

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