Bradlee Harrison
Radar Signal Processing Final Project

Passive Radar Signal Processing

Description

The objective of this project is to explore the steps of passive radar signal processing. A passive radar, as described by [1], is a radar that relies on a transmitter external to its own system. This kind of radar can be called passive bistatic radar, passive covert radar, or passive coherent location.

Passive radar can have several applications. Some uses for short range passive radar include detecting vehicles or smuggler drones in border areas detecting flying objects in the vicinity of small airports [2]

Illuminators

Because passive radar does not generate its own waveform, a passive radar system relies on another transmitter to provide the signal source. This is called an illuminator of opportunity [1].

Examples of potential illuminators of opportunity used in passive radar include:

- Broadcast stations: FM Radio [3] [4], ATSC [5], DAB/DVB-T [6][7]
- Cellular networks: 3G [8], 4G [9], 5G [2]
- Wi-Fi: 2.4GHz and 5GHz [10]
- Satellite systems: GPS [11], GLONASS, Galileo [12]

When using an illuminator of opportunity, typically a dedicated reference receiver channel is required in addition to the surveillance receiver because the transmitted signal is not known beforehand, but there are cases in which the original signal can be reconstructed, especially when using digital transmissions [12].

DAB Digital Audio and DVB-T Digital Television are common illuminators of opportunity used in passive radar [1]. A unique property of working with digital signals such as DVB-T and ATSC is that it is possible to obtain the reference signal without having a separate receiving channel for this purpose by decoding the bitstream and remodulating/synthesizing it back [5]. As a result, a passive radar system can function using only a single channel receiver. However, in the case of the 5G standard, it is not possible. [2]

Cellular networks such as 3G, 4G, and 5G can also be examined for passive Radar. 5G passive radar is currently only theoretical and no systems exist yet. Challenges emerge due to 5G transmissions being content-dependent, but there is a possibility of using the 5G periodic synchronization signal block for passive radar operation when the 5G data transmission is inactive [2]

Cross-Correlation

Cross-correlation is a popular method for passive radar target detection [13]. In cross-correlation based detection, signals from two sources are correlated: a surveillance antenna based on the target echo, and a reference antenna signal based on the original signal transmitted.

The cross-ambiguity function (CAF) is the standard process for calculating the time-delay of arrival between signals and is necessary for passive radar systems to detect and locate targets. There are many possible algorithms for calculating the cross-ambiguity function, including different types of windowing, decimation, doppler shift, and sampling rates [13].

Clutter Filtering

Various clutter removal algorithms exist with tradeoffs between computational complexity, efficacy, and difficulty of implementation. Clutter filtering algorithms can be iterative, running on iterations of previous processing intervals and adapting to the measurements over time. These methods include the Least Mean Squares and Normalized Least Mean Squares, Recursive Least Squares, and Least Square Lattice Filters [1]. Clutter filtering methods can also be block-based, such as the Least Squares Matrix solution, also known as the Extensive Cancellation Algorithm [1].

Localization and Target Tracking

In passive radar, due to the bistatic nature, localization and target tracking is more complicated than in active radar [14]. The time delay measured in passive radar corresponds to the bistatic range, which is the difference between the path that the signal travels. For the surveillance signal, the signal travels from the transmitter to the target and back to the receiver. For the reference signal, the signal travels from the transmitter to the receiver. These two positions between the transmitter and receiver are the foci of an ellipse of possible locations [12], which creates nonlinear behavior and uncertainties when applied to object localization and tracking. Issues such as ghost targets can appear due to potential ambiguities and false alarms [14]. Nonetheless, localization and target tracking approaches can use methods such as the Extended Kalman Filter to model motion and locate objects [14].

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FM Radio: Waveform Analysis

FM Radio is the transmitter I chose to cover in depth, due to the strong signal power used in the transmitters and the continuous operation of several stations making it very available and accessible.

In broadcast FM passive radar, typically fast pop or rock radio stations are used due to the higher bandwidths and more stable signal content [1]. To test some of this, I collected FM Radio data using an RTL-SDR from a single antenna from three different stations at 100.5 MHz, 102.7 MHz, and 104.1 MHz. 100.5 MHz is a rock radio station and 102.7 MHz and 104.1 MHz are pop radio stations.

The data was collected using GNU Radio with an RTL-SDR block and file sink that stored the data as characters with real and imaginary components interleaved. The setup and results can be seen in Figure 1 and 2.

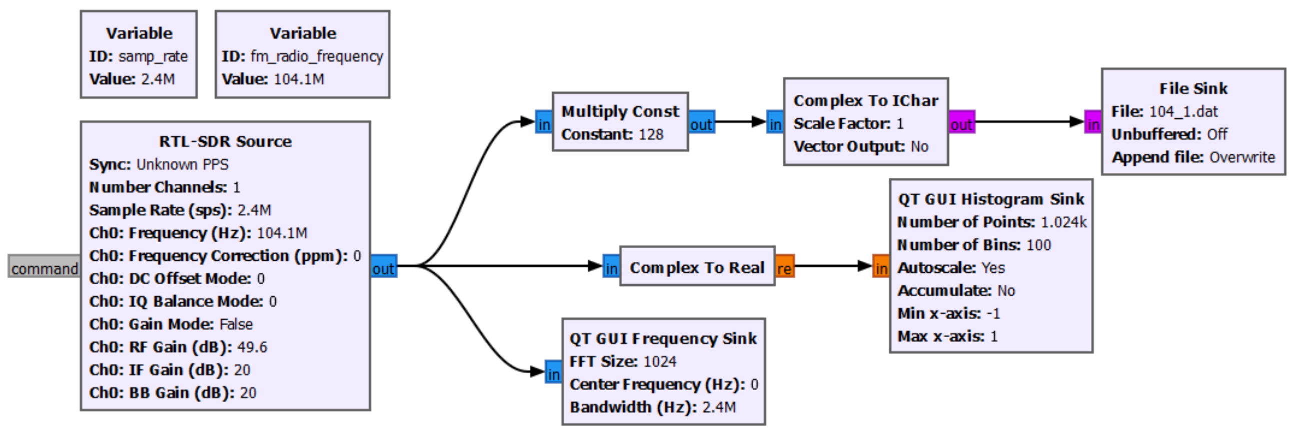

Figure 1. Flowgraph collecting data from 104.1 MHz channel.

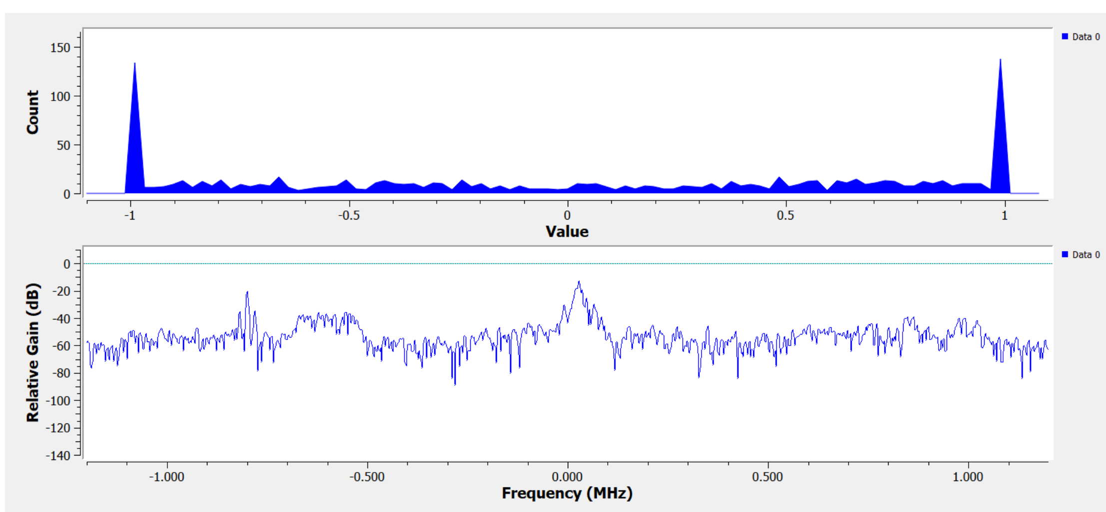

Figure 2. Histogram of data collected and frequency content of samples collected for 104.1 MHz channel.

I used a sample rate of 2.4 MS/s, which included frequency content from other channels. To reduce interference from other channels, I passed the data through a low pass filter. I used a Hamming window low-pass filter with an order of 30 and cutoff frequency 480 kHz. To compare the signals, I plotted the frequency and autocorrelation response for one second of data, which can be seen in Figure 3.

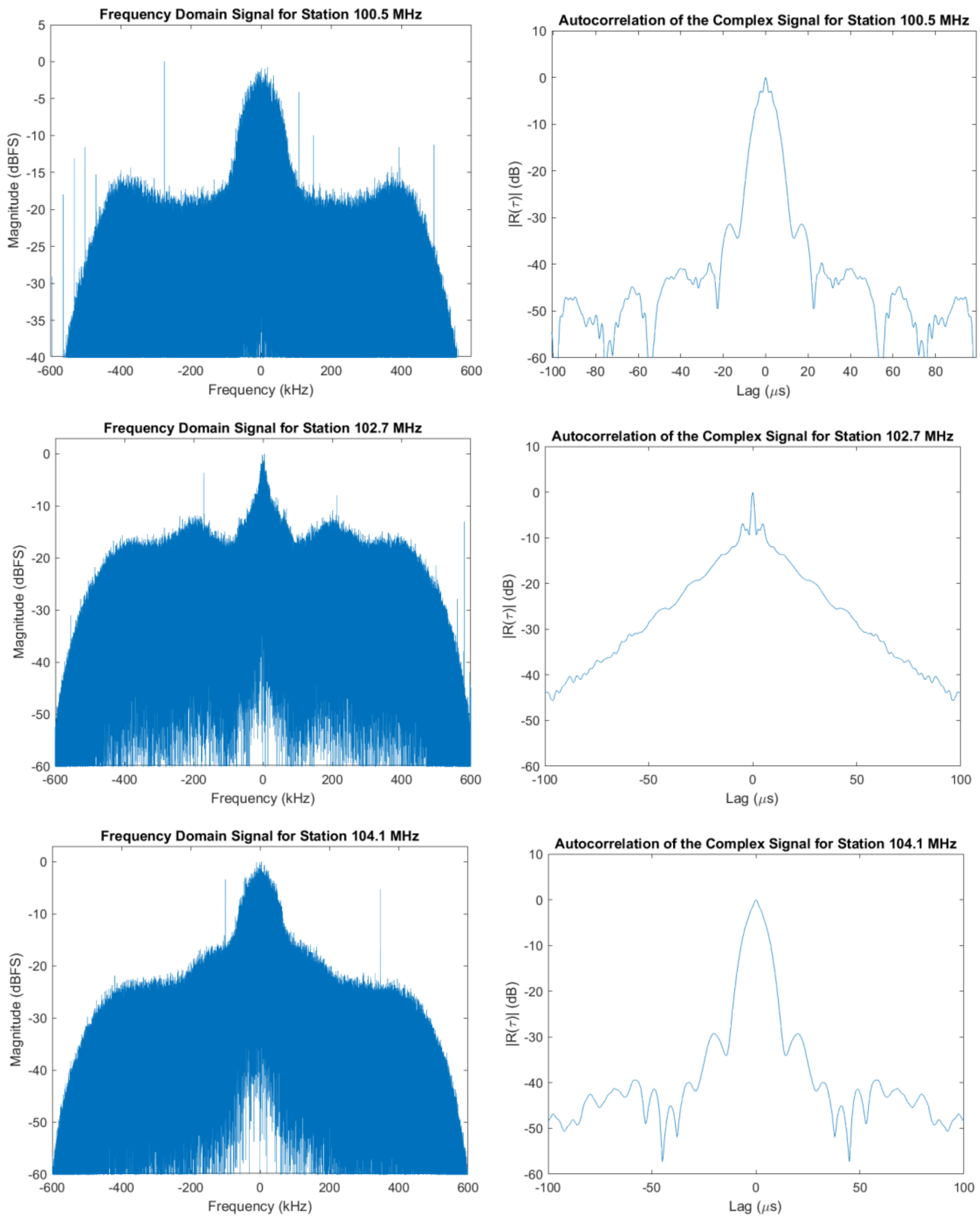

Figure 3. Frequency Response and Autocorrelation Response for 2 seconds of data from stations at 100.4 MHz, 102.7 MHz, and 104.1 MHz.

The frequency response of the three signals are similar, as they are all high-quality FM broadcasts. In comparison to the others, the 102.7 MHz channel has the narrowest bandwidth, and has worse sidelobes in the autocorrelation response than the other channels, so it is likely not ideal for a radar waveform. The 104.1 MHz channel has decent bandwidth and the sidelobes in the autocorrelation response at $\pm 20\mu$s lag are -30 dB, which is significantly good performance. The 100.5 MHz channel has even better peak-to-sidelobe response of -31.5 dB at $\pm 17.5\mu s$ lag.

It is important to note that these measurements only correspond to a single instant of time, and due to the nature of the broadcasts' constantly changing signal content, this does not fully represent the capability of the overall broadcast.

For a second metric of the waveforms' performance, a good measure may be the bandwidth over time, so I calculated the 3dB bandwidth every 0.1s for the three signals over 30 seconds of time. The bandwidth over time changed significantly with the signal, but over the interval that was sampled, the 104.1 MHz channel has the best bandwidth on average.

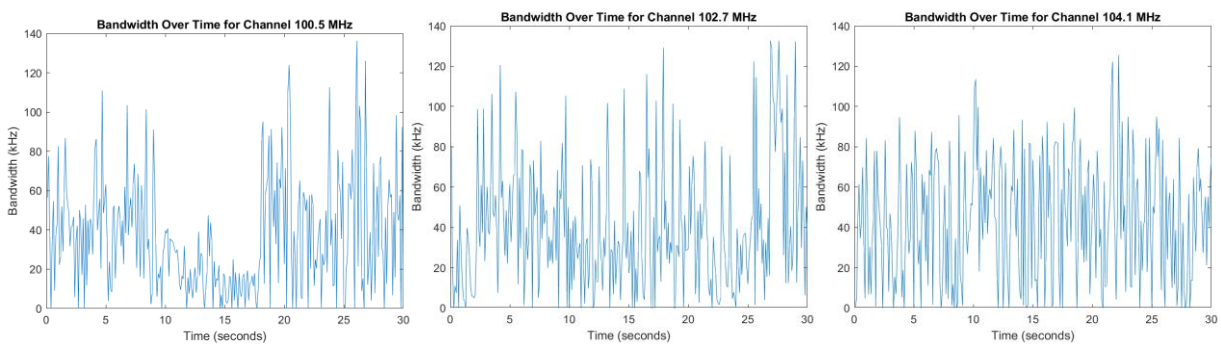

Figure 4. Bandwidth over time measurements

Cross Ambiguity Function

Typically in a passive radar system, waveforms will be received at two or more antennas, with one signal being used for reference and another for surveillance. Using both reference and surveillance signals, a cross-ambiguity function (CAF) can be calculated to create a range-velocity map where detection algorithms can be used to detect targets.

The formula for the CAF is [1]:

$$\psi(m,k) = \sum_{n=0}^{N-1} x_e(n) \cdot x_r^*(n-m) \cdot \exp\left(-j\frac{2\pi}{N}kn\right)$$

Where $x_e(n)$ is the echo signal received from a surveillance source, $x_r(n)$ is the reference signal, n is the index of each time delay, and k is the index of each frequency bin.

To begin the analysis, I computed the CAF between two identical band-limited Gaussian noise sources, as shown in Figure 5. Given that the waveforms are identical and no frequency or doppler shift is present, the CAF contains a single peak at 0 delay and 0 frequency shift. This represents the point where the waveforms align, and the function reduces to the normal self-ambiguity function.

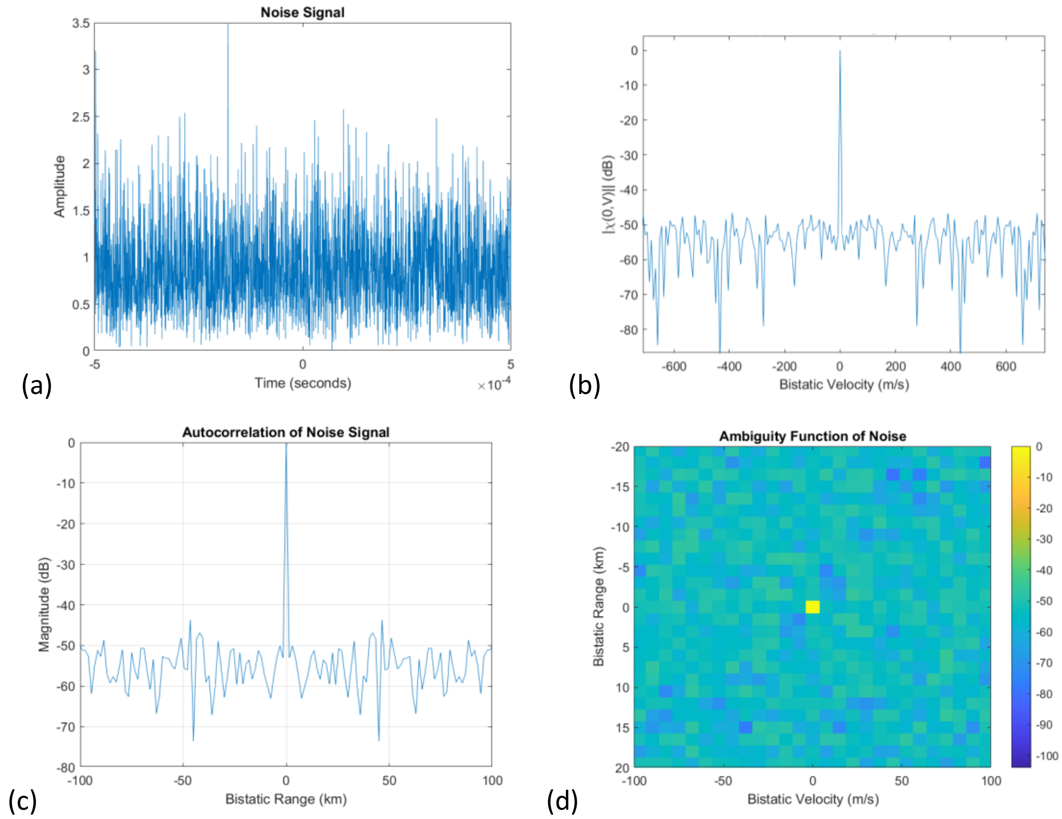

Figure 5. (a) Noise Signal (b) 0-Range Cut of Ambiguity Function (c) 0-Velocity Cut of Ambiguity Function (d) Top View of Ambiguity Function

I then calculated the self-ambiguity functions of the three waveforms for the first CPI. This can be seen in Figure 6. The differences caused by sidelobe and noise fluctuations show that the 102.7 MHz channel signal clearly has worse performance compared to the others, with sidelobes and noise fluctuations that spread throughout the entire spectrum. Again, the 100.5 MHz channel has the best performance in this interval.

Following the self-ambiguity analysis, I used a simple model to create a second signal, x_e from the reference signal x_r, adding an echo component with a doppler shift, f_d, and delay, d, to simulate a theoretical reflected echo signal being produced by the target with some attenuation, α.

$$x_e(t) = x_r(t) + \alpha x_r(t-d)e^{j2\pi f_d t}$$

For the first CPI of the three waveforms, I calculated the CAF of the two signals x_e and x_r, for α = 0.5 and α = 0.05, which correspond to a 6 dB and 26 dB decrease in target signal power. For the doppler shift and delay I set f_d = -50, and $d = 30$ samples, which corresponds to a bistatic range of 30km and bistatic velocity of ~150 m/s at the sample frequency 480kHz and carrier frequencies 100–104MHz. The results can be seen in Figure 7. The peaks around 0 velocity and 0 range show the direct-path signal being included. In all three functions for α = 0.5, the targets are visually detectable at the correct range and velocity. However, in the more challenging scenario with α = 0.05, the target is less clear. The direct path interference includes high power sidelobes that make the target detection more difficult and would potentially cause more false alarms.

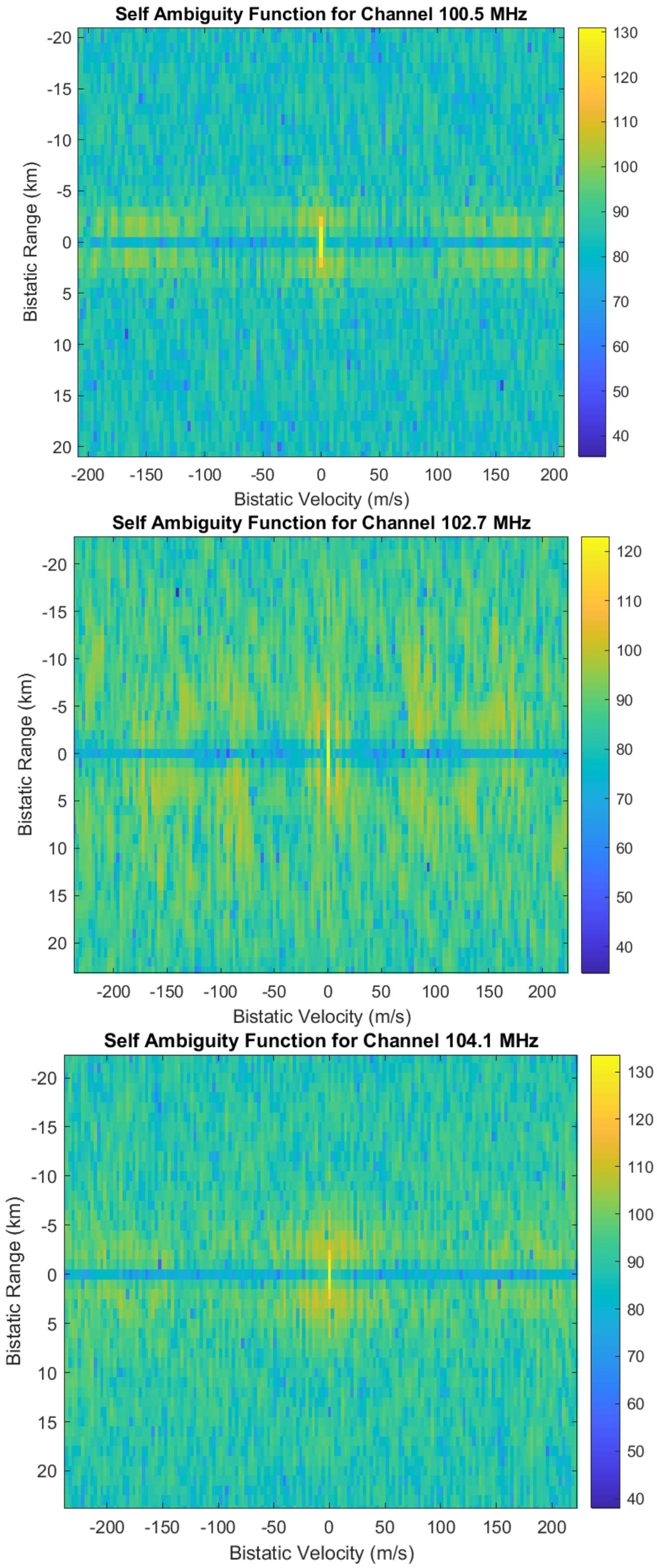

Figure 6. Self Ambiguity Functions for first CPI of 100.5, 102.7, and 104.1 MHz channels

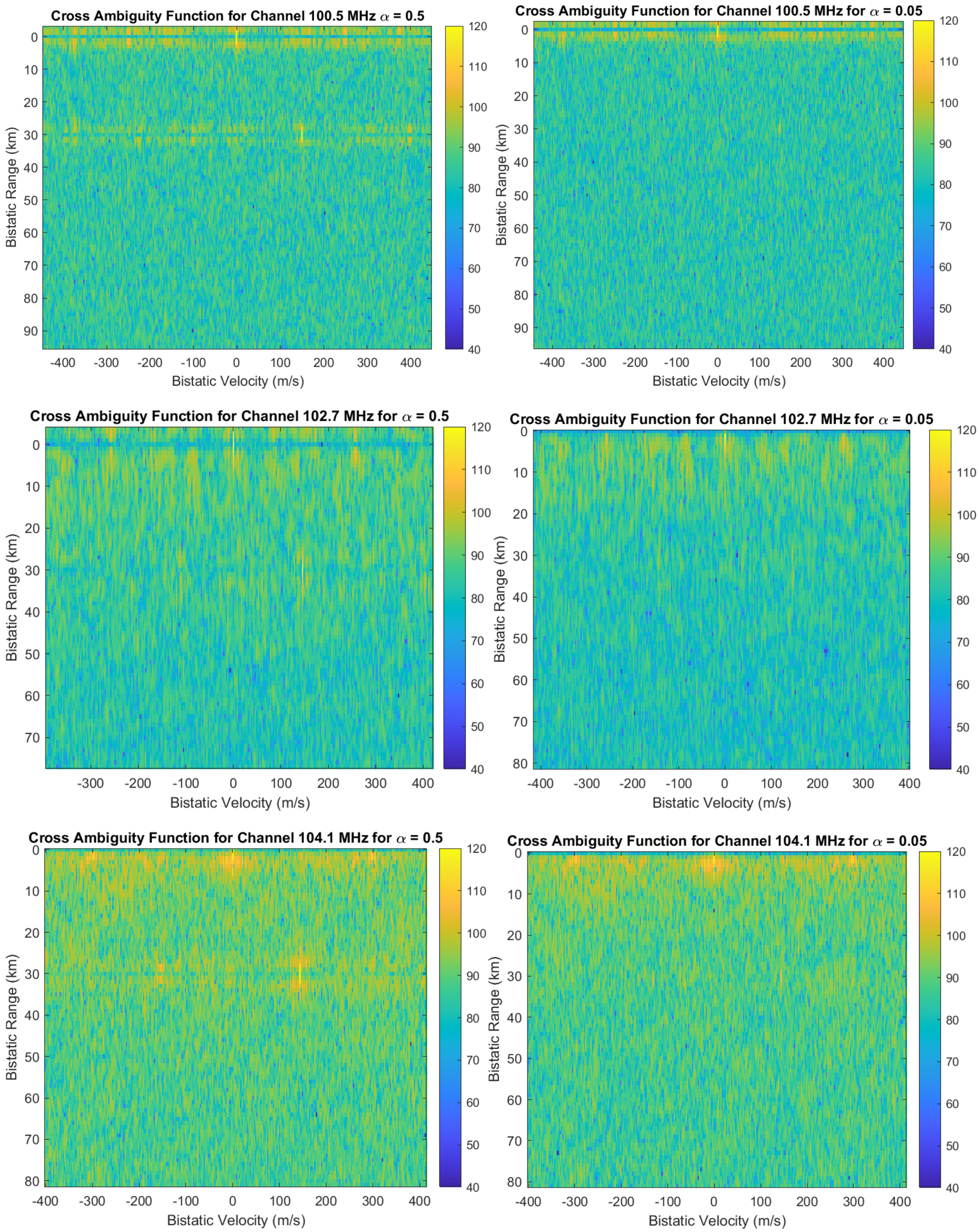

Figure 7. Cross Ambiguity Functions between simulated x_e and x_r for first CPI for of 100.5, 102.7, and 104.1 MHz channels

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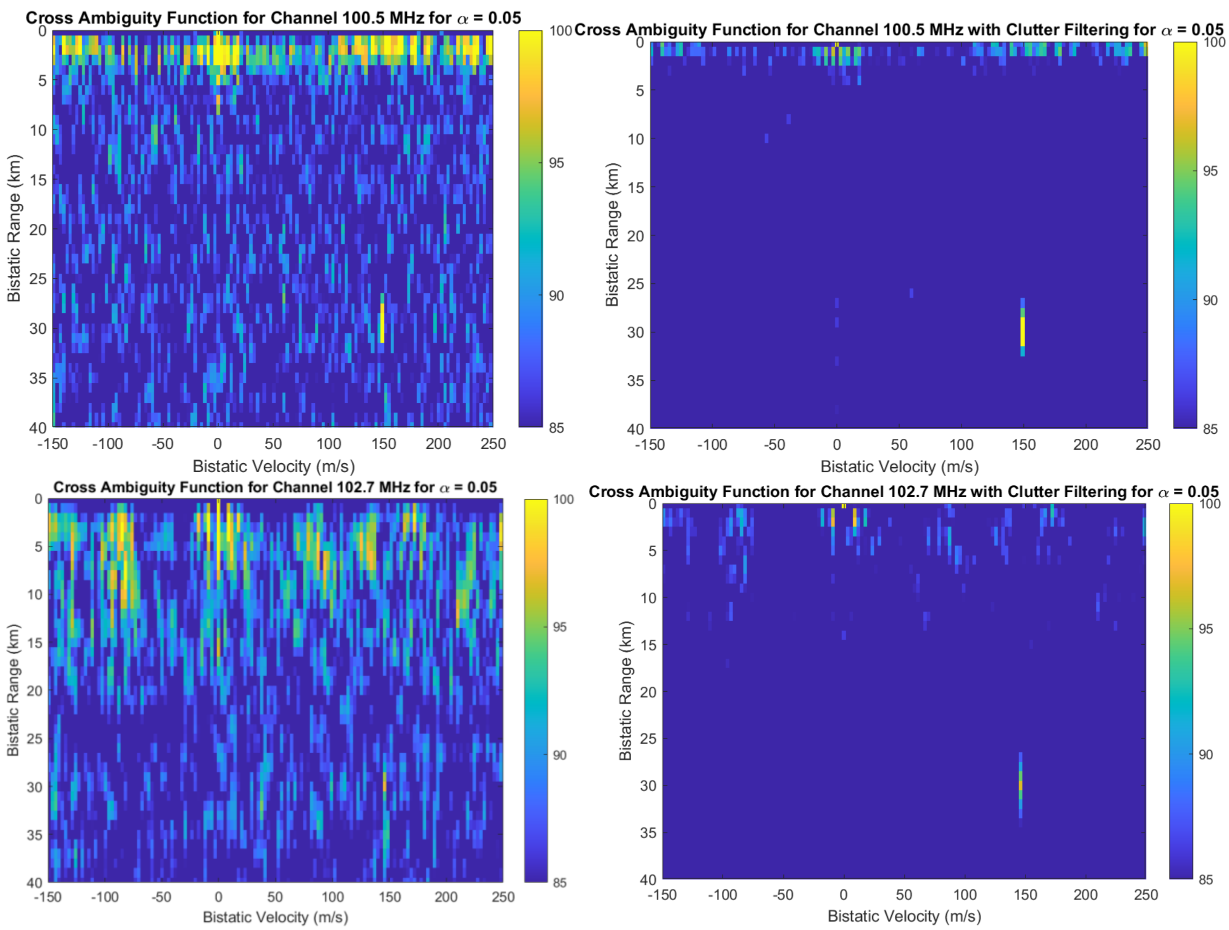
Clutter Removal

As we see in the previous ambiguity function example, direct path interference and clutter can make it more difficult to detect objects. As a result, conventional passive radar systems use clutter removal algorithms to filter interference from the reference signal.

I used clutter removal between the simulated x_e and x_r signals in the range response, with the objective of removing positive-delay reflections of the reference signal. The results can be seen in Figure 8. This time, I have restricted the color limits to focus on the detections itself. The limit ranges from 85 dB to 100 dB. In all three scenarios, applying clutter filtering has greatly cleared up the CAF. After the clutter filtering has been applied, the map shows only the target and residual interference in all three scenarios.



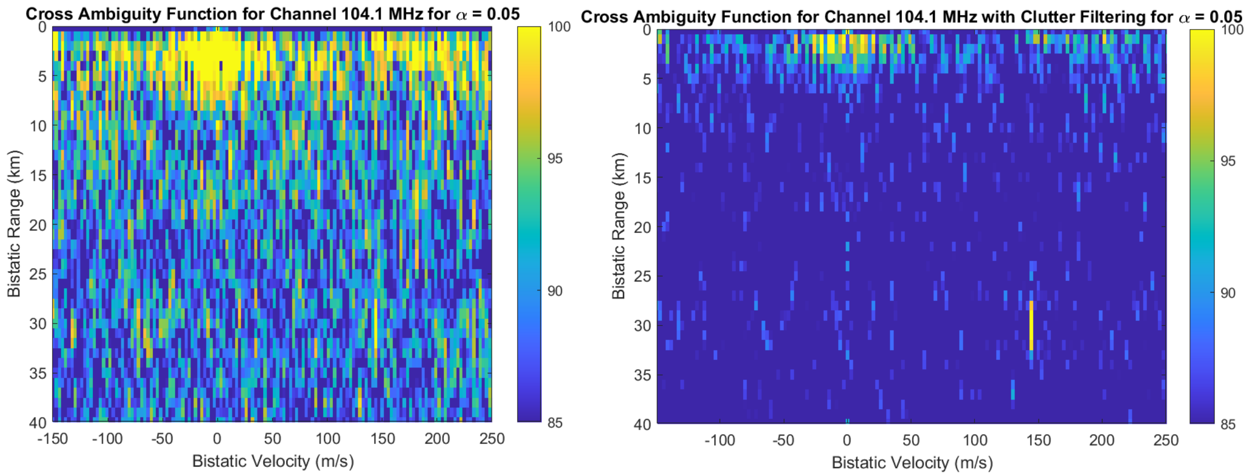


Figure 8. Cross Ambiguity Functions between simulated x_e and x_r before and after clutter removal for first CPI for of 100.5, 102.7, and 104.1 MHz channels. Color limits range from 85 to 100 dB.

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