Authors' Replies to Comments by Reviewer 1

First of all, the authors would like to thank you, Reviewer 1, very much for your time and effort spent in going through this manuscript. Your suggestions have greatly helped us in sharpening and clarifying the manuscript's basic argument. Below we respond to your specific comments point by point.

***COMMENT 1.1**: Please elaborate on how to determine the max range and max Doppler. Can we have both high max range and high max Doppler in this passive radar design through overlapping signal blocks?*

Reply: In passive radar systems, the maximum range and maximum Doppler frequency are crucial parameters that directly affect the system's performance. The range and Doppler characteristics are determined by the characteristics of the transmitted signals and the geometry of the radar setup, the formula is derived as follows:

$$R_t R_r = \sqrt{\frac{P_t G_t G_r \lambda^2 \sigma L}{(4\pi)^3 P_r K T_0 B F}}$$

$$f_d = \frac{2v_t}{\lambda} \cdot \cos\left(\frac{\beta}{2}\right)$$

where P_r, P_t are the received signal power, radiation source transmit power. B, F, L are the receiver's effective bandwidth, the receiver's noise figure and system loss, T_0 = 290K, λ is the wavelength, K is the Boltzmann's constant, G_r is the receiver antenna's gain, R_t is the distance between the target and the radiation source, R_r is the distance between the receiver and the target, and σ is the radar cross section area (RCS) of the target, v_t is the relative speed between the radar and the target. The angle between the target transmitter and target receiver segments, denoted with β, is called the bistatic angle.

The maximum range of a passive radar system depends on several factors, including the wavelength of the signals used, the power of the signal, the sensitivity of the receiver, and the processing capabilities of the system. The range resolution is inversely proportional to the bandwidth of the received signal. A larger bandwidth allows for better range resolution. The maximum Doppler frequency is influenced by the carrier frequency of the received signal and the maximum relative velocity between the radar and the target. Higher carrier frequencies and faster relative velocities result in higher Doppler frequencies.

Overlapping signal blocks may allow for improved range and Doppler by using multiple signals with different characteristics simultaneously. However, this approach requires sophisticated signal processing techniques to handle the simultaneous reception of multiple signals. Achieving both high maximum range and high maximum Doppler in a passive radar design through overlapping signal blocks is challenging, and there are inherent trade-offs that need to be considered. Here are some key points to keep in mind:

- **Bandwidth Considerations:** Increasing the bandwidth of the received signals can improve Doppler resolution but might reduce range resolution. This is a common trade-off in radar systems known as the range-Doppler ambiguity. Overlapping signal blocks may provide more information, but the available bandwidth and the characteristics of the signals limit the extent to which both high range and high Doppler resolution can be achieved simultaneously.
- **Signal Processing Complexity:** Overlapping signal blocks introduce complexities in signal processing. Extracting both range and Doppler information from multiple signals requires sophisticated algorithms and can increase computational requirements.
- **Interference and Calibration Challenges:** Overlapping signals can lead to interference, making it challenging to separate and accurately process individual signals. Calibrating the system to handle multiple signals simultaneously is crucial. Interference can impact both range and Doppler measurements, potentially degrading the overall system performance.
- **Hardware Limitations**: The hardware characteristics of the receiver and antenna system play a significant role. The system must be capable of handling a wide range of frequencies and processing multiple signals simultaneously.

The above discussion has been included in Section 2.1. Radar System Analysis.

COMMENT 1.2*: If the traditional radar range and Doppler dilemma still applies, are there any ways to mitigate the dilemma in the passive radar setup? Please discuss this in the paper.*

Reply: Thanks for this suggestion. We have clarified these in the Section 2.2 and Eq. (9) and (10). The range-Doppler dilemma is a fundamental challenge in radar systems, including passive radar setups. This dilemma arises from the inherent trade-off between range resolution and Doppler resolution, and it is often challenging to achieve both simultaneously. While the dilemma remains, there are several strategies and technologies that can be employed to mitigate its impact in passive radar setups:

- **Adaptive Waveforms:** Implement adaptive waveform strategies, employ waveforms that can adapt to the changing environment and requirements. Adaptive techniques, such as frequency-modulated continuous-wave (FMCW) radar, can provide flexibility in trading off range and Doppler resolutions.
- **Multiple Input Multiple Output (MIMO) Techniques:** Utilizing MIMO techniques, employ multiple antennas and exploiting spatial diversity can help improve both range and Doppler resolution. MIMO techniques enable the use of multiple observations to enhance system performance.
- **Advanced Signal Processing:** Using advanced signal processing algorithms, implement sophisticated signal processing techniques, such as time-frequency analysis methods (e.g., Short-Time Fourier Transform or Wavelet Transform), to extract both range and Doppler information from received signals.
- **Wideband Signals:** Increasing the bandwidth of the received signals can enhance both range and Doppler resolution. Wideband signals allow for better

discrimination between targets at different ranges and velocities.

Some of the above discussion has been included in Section 2.3. Range-Doppler Processing

COMMENT 1.3*: The author chose FM radio waveform. The carrier frequency of FM is low. Therefore, the ambiguous Doppler velocity is high.*
Reply: We fully agree with you that the lower carrier frequency of FM leads to high ambiguous Doppler speeds velocity. In addition, the lower PRF in radar and ambiguity sidelobe in the transmit signal can lead to ambiguous Doppler velocity measurements. In our subsequent work, we will consider the use of mismatched filtering and some preprocessing operations to solve this problem.

COMMENT 1.4*: FM has no cyclic prefix. If a waveform with cyclic prefix is chosen, can the overlapping FFT design still work? Please explain since this paper claims generality of passive waveforms.*
Reply: The cyclic prefix is a feature commonly used in communication waveforms, such as those in Orthogonal Frequency Division Multiplexing (OFDM) systems, to mitigate the effects of channel fading and inter-symbol interference. It is typically not a characteristic of Frequency Modulation (FM) waveforms, which do not include a cyclic prefix. The use of a cyclic prefix can be beneficial in certain aspects, such as improving robustness against multipath propagation.

Our proposed clutter suppression and distance Doppler scheme is also applicable to this type of waveforms, but it needs to be corrected according to the characteristics of the waveforms in use. Take the Digital Terrestrial Multimedia Broadcast (DTMB) signal as an example, which uses the cyclic extension structure of the PN sequence as a prefix, and if this feature is not handled, it will produce a number of regular secondary peaks in the result of the cross-correlation computation, which will have an effect on the detection of the target. In engineering, header zeroing is often used to process the reference signal. For this type of signal, our design idea is: first, use the standard signal frame data to highlight the header with the captured reference channel in the inter-correlation operation; then, search for the header region in the inter-correlation result; and lastly, zero the header region in the searched signal.

We have included these discussions in Section 3.2. GPU Parallel Algorithm for Range-Doppler Processing.

Finally, the authors are again grateful to you, Reviewer 1, for your time and effort to make this paper a much better one.