Understanding the Signal Structure in DVB-T Signals for Passive Radar Detection

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***Abstract*—This paper provides a detailed overview of Digital Video Broadcasting Terrestrial (DVB-T) signal structure and the implications for passive radar systems that use these as illuminators of opportunity. In particular, we analyze the ambiguity function and make explicit its features in delay and Doppler in terms of the underlying structure of the DVB-T signal. Ambiguities will be managed via the development of a set of mismatched filter weights that will be applied to the reference signal prior to range-Doppler map formation. The development of the mis-matched filter is based on previous work with an extended improvement for ambiguity peak reduction a wider variety of DVB-T signals.**

I. Introduction

Much attention has been given to passive radar systems of late. Many signals have been analyzed and studied as possible illuminators of opportunity including Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB), FM radio, cellphone base-stations, and various satellite systems [1], [2], [3], [4], [5], [6]. DVB-T digital television signals provide an especially attractive opportunity for radar. Digital television transmitters offer a powerful, well-defined signal with minimal cost to the radar user. The signal has sufficient bandwidth to provide reasonable precision in range and is noise-like allowing for good range compression and Doppler estimation [7]. Analysis and methods for improvement of passive radar systems using 2k mode DVB-T sources have been studied previously [4], [5], [8]. In this paper, we look at these approaches, performing a cross-correlation of the received channel signal with a mismatched reference signal chosen to reduce the effects of the ambiguity peaks, and offer an explanation of some problems in current passive radar systems and how this analysis applies to the system described in [1]. Because we are focusing on this system, we concentrate on 8k mode operation for the DVB-T signals.

II. DVB-T signal overview

DVB-T signals have a very specific structure designed to provide for good reception of television signals as detailed in [9]. Only a brief summary of the relevant portions influencing a passive radar system will be given here.

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A. OFDM Frame Structure

The DVB-T signal is an Orthogonal Frequency Division Multiplexed (OFDM) signal with either 2k or 8k subcarriers depending on the operating mode. An OFDM symbol has duration T_S and consists of K_C active carriers. Symbols are organized into frames, with each DVB-T frame consisting of 68 OFDM symbols. A super-frame consists of four frames and is used to match the OFDM signaling with the framing for the error control coding in the system. The OFDM symbols carry data belonging to three different types: 1) the MPEG-2 video data stream, 2) the DVB-T transmission parameter signal (TPS), and 3) pilots.

1) Data Definition: The MPEG-2 stream first passes through a series of stages including bit-randomization, outer-coding, and inner-coding before being mapped into the signal constellation. This process results in the information appearing on these carriers as random data to the radar system and thus noise-like. This also leads to the flat spectrum of the signal as seen in Fig. 2. The data carriers are modulated with Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM), or 64-QAM depending on the operating mode.

2) Transmission parameter signal (TPS) Definition: The TPS carriers convey information about the parameters of the transmission scheme. The carrier locations are constant and defined by the standard and all carriers convey the same information using Differential Binary Phase Shift Keying (DBPSK). The initial symbol is derived from a Pseudorandom Binary Sequence (PRBS).

3) Pilot Definition: The pilot symbols aid the receiver in reception, demodulation, and decoding of the received signal. Two types of pilots are included: scattered pilots and continual pilots. The scattered pilots are uniformly spaced among the carriers in any given symbol. In contrast, the continual pilot signals occupy the same carrier consistently from symbol to symbol. The location of all pilot symbol carriers is defined by the DVB-T standard. Fig. 1 illustrates the pilot spacing for a DVB-T OFDM frame where carriers are indexed horizontally and symbols are indexed vertically. The pilots are based on a PRBS and are BPSK modulated at a boosted power level, $\frac{16}{9}$ times greater than that used for the data and TPS symbols.

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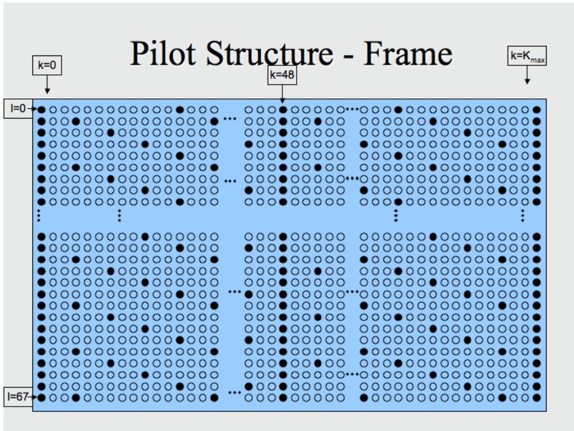

Fig. 1. Pilot structure in the DVB-T OFDM frame

B. Signal Definition

The structure of the signal is given by the following equation:

$$s(t) = Re\{e^{j2\pi f_C t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=0}^{K_C-1} c_{m,l,k} \cdot \psi_{m,l,k}(t)\} \tag{1}$$

where

$$\psi_{m,l,k}(t) = \begin{cases} e^{j2\pi \frac{k'}{T_U}(t-\Delta-lT_S-68mT_S)} & t_1 \le t \le t_2 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

and

- k denotes the carrier number
- l denotes the OFDM symbol number
- m denotes the OFDM frame number
- $c_{m,l,k}$ are the complex-valued symbols
- K is the number of carriers
- K_C is the number of active carriers
- f_c is the carrier frequency
- T_U is the duration of the useful part of the symbol i.e. the part of the symbol excluding the guard interval
- T_S is the symbol duration including the guard interval
- Δ is the guard interval duration
- $t_1 = (l + 68m)T_S$
- $t_2 = (l + 68m + 1)T_S$

Our interest is focused on the Australian DVB-T standard [9], [10] where the key distinction is a reduction in channel bandwidth to 7 MHz. The spectrum of a simulated baseband DVB-T signal is shown in Fig. 2. The flat, noise-like shape of the spectrum is evident.

III. Radar Ambiguity Function

The radar ambiguity function is a 2D autocorrelation function given by the following [11]:

$$\chi(\tau, f_d) = \int_{-\infty}^{\infty} s(t) \cdot s^*(t+\tau) e^{j2\pi f_d t} dt \tag{3}$$

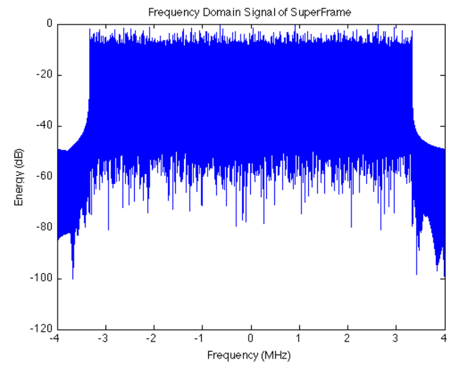

Fig. 2. Spectrum of DVB-T Signal

TABLE I
Relevant Parameters

Parameter	Value
K	8192
K_C	6817
T_U	1024 μs
Guard Interval Δ/T_U	1/4,1/8,1/16,1/32
Carrier Spacing $1/T_U$	976.6 Hz
Bandwidth $(K_C - 1)/T_U$	6.65625 MHz

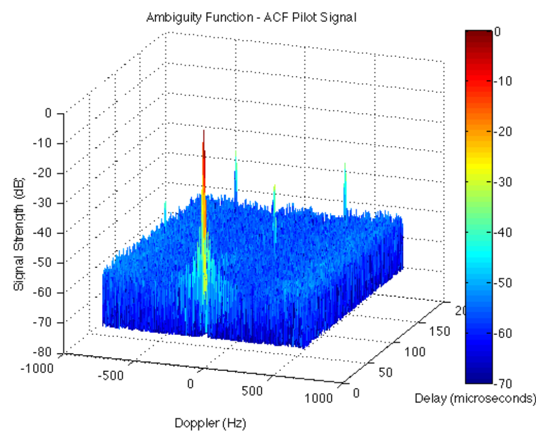

Fig. 3. Ambiguity Function of DVB-T Signal

where $s(t)$ is the LOS reference signal, and τ and f_d are the delay and Doppler hypotheses respectively.

The processing is implemented as in [12]. An example from the simulation is given in Fig. 3. Several ambiguities are seen aside from the peak at zero-delay and zero-Doppler. To understand the source of these ambiguities, we must look more closely at the structure of the DVB-T signal, namely the pilot signals inserted into the OFDM structure.

In Fig. 4 we highlight the ambiguities by plotting the ambiguity function using the signal with all information removed save the pilots. Repeating bands across both delay and Doppler dimensions are obvious in the plot. The pilots are spaced very regularly in both time and frequency and the spacing of the ambiguities can be determined from these two spacings.

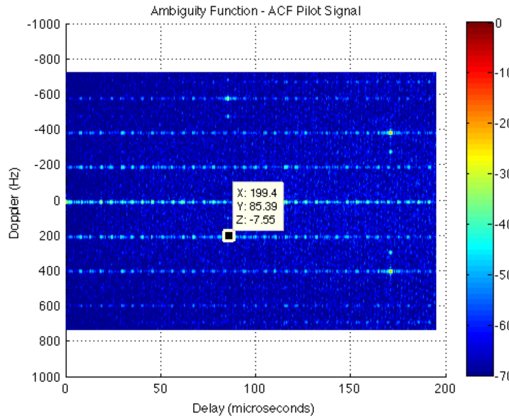

Fig. 4. Ambiguity function of pilot-only signal

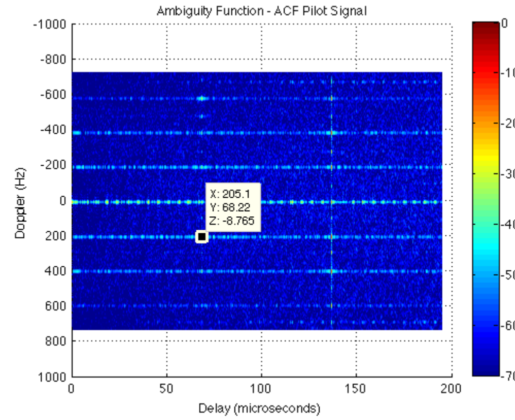

Fig. 5. Ambiguity Function of Pilot-only Signal with modified pilot spacing of 15 carriers

A. Ambiguities in Delay - Pilots Spaced in Frequency

The spacing of the scattered pilots is constant within a symbol. Scattered pilots are placed every twelve carriers. For the Australian 8k-mode DVB-T signal, this corresponds to 11.719 kHz ($\frac{12}{T_U}$) and causes ambiguities to arise every 85.3μs ($\frac{T_U}{12}$) in delay.

To see why the ambiguities appear in delay, we must think of the time-domain signal. The scattered pilots correspond to sinusoids evenly spaced by $\frac{12}{T_U}$ Hz. The ambiguity function for the scattered pilots at zero-Doppler becomes

$$\chi(\tau, f_d) = \int_{-\infty}^{\infty} \sin(2\pi f_q t)\sin(2\pi f_q t + 2\pi f_q \tau)dt \quad (4)$$

where

$$f_q = \frac{12}{T_U} \cdot q \quad (5)$$

and q is an integer. In the cross-correlation at a delay corresponding to $\frac{r}{f_q}$, the ambiguity function becomes

$$\chi(\tau = \frac{r}{f_q}, f_d) = \int_{-\infty}^{\infty} \sin(2\pi f_q t)\sin(2\pi f_q t + 2\pi r)dt \quad (6)$$

and because r is an integer we get maximal correlation at these delays (i.e. clear peaks are noticeable at $85.3\mu s$ and $170.6\mu s$ in Fig. 4).

To verify this we altered the carrier spacing in our simulation. Fig. 5 shows the resulting ambiguity function with a modified pilot spacing of fifteen carriers, or 14.649 kHz. The ambiguities now appear every 68.26μs in delay.

B. Ambiguities in Doppler - Pilots Spaced in Time

The scattered pilots are also spaced regularly across symbols. Every fourth symbol sees the scattered pilots occupying the same carrier. For the signal used, which has a guard interval (Δ/T_U) of $1/4$, this corresponds to scattered pilot spacing across symbols of 5.12 ms and causes ambiguities to arise every 195.3 Hz in Doppler. This is seen as obvious stripes in Doppler in Fig. 4.

Again, we verified the effects of the pilots by altering the symbol duration achieved by changing the guard interval. Fig.

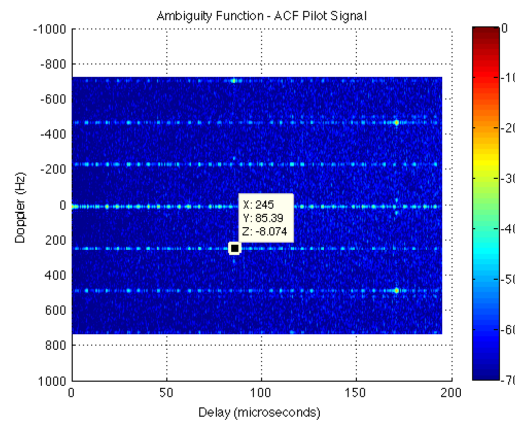

Fig. 6. Ambiguity Function of Pilot-only Signal with guard interval of 1/32

6 shows the ambiguity function with a guard interval of $1/32$. This results in a shorter symbol duration and shorter scattered pilot spacing across symbols of 4.61 ms. The resulting doppler ambiguities are spaced 217.0 Hz apart.

Another feature in Doppler to note is that the coincidence of ambiguities in delay and Doppler result in main peaks separated by 781 Hz. This is consistent with wrapping over the length of a symbol including the guard interval (i.e. $\frac{1}{T_U + T_U/4}$).

Note: We expect to find ambiguities arising from frame and super-frame structure, but these are most likely outside of our processing scale.

C. Other Ambiguities

As shown in [4], [5], there are other ambiguities that arise at larger delays. Fig. 7 shows a larger delay-Doppler map which includes some of these ambiguities. [4], [5] refer to the three regions as intra-symbol pilot peaks, guard interval peaks, and inter-symbol pilot peaks. We have explained the intra-symbol pilot peaks in the previous subsections.

1) Guard Interval Ambiguities: The next occurrence of ambiguity peaks is caused by the guard interval which is a repeat of the end of the DVB-T symbol. This occurs at a

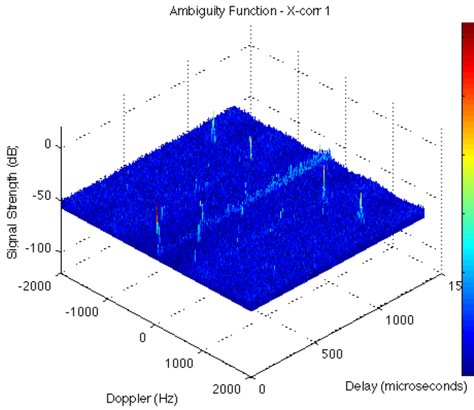

Fig. 7. Ambiguity Function of full DVB-T Signal in 8k-mode operation with a guard interval of $\frac{1}{4}$

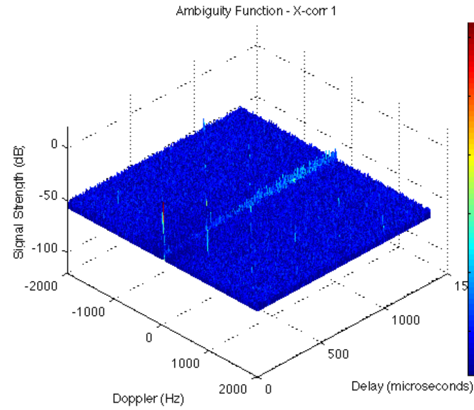

Fig. 8. Ambiguity Function of full DVB-T Signal in 8k-mode operation with a guard interval of $\frac{1}{32}$

delay of T_U, or $1024\mu s$ for the specified signal. We also note that the power of these peaks is dependent on the length of the guard interval. If the guard interval is longer then more repeated signal contributes to the correlation. If we compare signals with guard intervals of $\frac{1}{32}$ and $\frac{1}{4}$ respectively, then we would expect the peaks in the ambiguity function to differ by a factor of 8, or 18 dB. Fig. 7 and 8 show the ambiguity function for these two signals, and we see a difference in power exactly as expected. The signal with a guard interval of $\frac{1}{4}$ has peak power -12dB and the signal with guard interval of $\frac{1}{32}$ has peak power of -30dB, a difference of 18 dB.

2) Inter-symbol Ambiguities: The third region of ambiguity peaks is caused by the inter-symbol correlation of pilots. Because these arise from inter-symbol pilots and scattered pilots are repeated every fourth symbol, these ambiguities occur near a delay of $4T_S$, or $5.12ms$ for 8k-mode DVB-T signals with guard interval of $\frac{1}{4}$. This delay corresponds to a distance of greater than $1500km$, outside of the current range of interest for passive radar systems. Fig. 9 shows the ambiguity function for a 2k-mode DVB-T signal, and we see that these ambiguity peaks occur near $1ms$ delay and within the region of interest for a passive radar system. These ambiguities, though important for 2k-mode DVB-T signals, are not considered for 8k-mode DVB-T signals.

IV. Reducing Effects of Pilots in the Ambiguity Function

One approach for reducing the ambiguities is detailed in [4], [5] where a parallel processing technique consisting of three stages is employed to achieve a reduction in ambiguity peak power. The three stages are guard interval blanking, pilot equalization, and pilot blanking. The guard interval blanking reduces the ambiguities resulting from the guard interval. The pilot equalization reduces the ambiguities associated with the intra-symbol pilots. The pilot blanking reduces the ambiguities associated with inter-symbol pilots. These methods were only demonstrated for the 2k-mode DVB-T signals, and we show that a slight modification can eliminate these ambiguities for an 8k-mode signal as well.

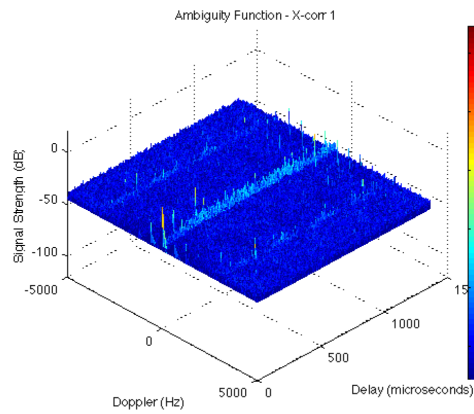

Fig. 9. Ambiguity Function of full DVB-T Signal in 2k-mode operation with a guard interval of $\frac{1}{4}$

These processing techniques replace the matched-filter approach of (3) with a mismatched-filter given by

$$\chi(\tau, f_d) = \int_{-\infty}^{\infty} s_r(t) s_h^*(t+\tau) e^{j2\pi f_d t} dt \qquad (7)$$

where $s_h(t)$ is a filtered DVB-T reference signal with the filter coefficients chosen to achieve the desired effect on the guard interval or pilot carriers. The reference signal is the LOS signal of the DVB-T transmitter. $s_r(t)$ is the received signal containing possible target information.

Here we first investigate the application of the technique described in [4], [5] to the 8k-mode signal. We then propose an improvement for the pilot equalization stage based on consideration of the power contained in the pilots in the mismatched reference signal and the received signal. We demonstrate the efficacy of our new method for both 2k- and 8k-modes.

With respect to the 8k-mode signals, we first notice that the pilot blanking stage is unnecessary. As noted above, the ambiguity peaks associated with the inter-symbol pilots appear

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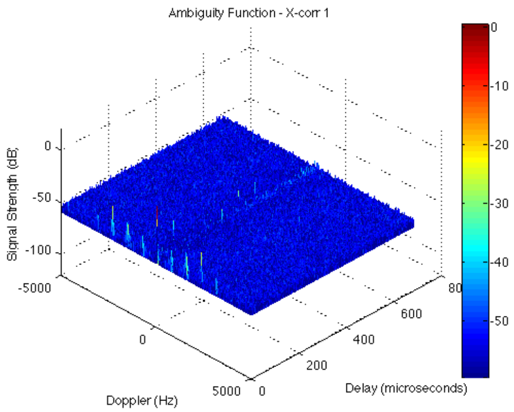

Fig. 10. Cross-correlation of full 8k-mode DVB-T signal with blanked guard signal

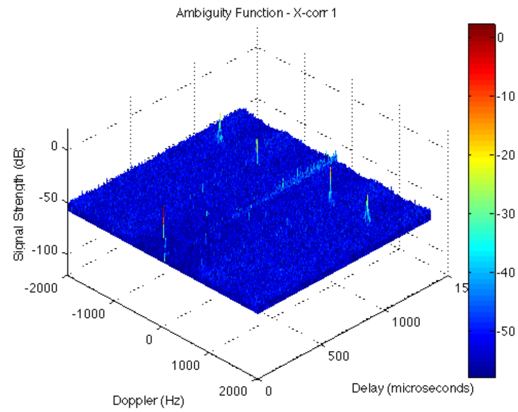

Fig. 11. Cross-correlation of full 8k-mode DVB-T signal with modified reference signal $s_{h_1}(t)$

at a delay of $5.12ms$, which is outside our region of interest.

Guard interval blanking allows us to move the guard interval peaks from a delay of $T_U = 1024\mu s$ to a delay of zero, as shown in Fig. 10. We therefore have a tradeoff with guard interval blanking: the guard interval can be left untouched in the reference signal and there will be ambiguity peaks at a delay of T_U, or the guard interval can be blanked and there will be ambiguity peaks at zero-delay.

Concentrating on the pilot equalization, we first apply the method of [4], [5] to the 8k-mode signal. The filtered reference signal, $s_{h_1}(t)$, is obtained by applying a filter to the LOS reference signal with a frequency response that reduces the pilot carrier tones to a power of unity. This method, while there is a reduction, does not eliminate the ambiguity peaks, as shown in Fig. 11. To eliminate these ambiguities, we use a filtered reference signal, $s_{h_2}(t)$, which is obtained by applying a filter to the LOS reference signal with a frequency response that reduces the power of the pilots to $\frac{9}{16}$. The resulting delay-Doppler plot is given in Fig. 12. A cross-sectional view of a particular ambiguity at $85.3\mu s$ delay and 200 Hz Doppler are given in Fig. 13. We see a reduction in power of 7 dB from -28.3 to -35.5 when using $s_{h_1}(t)$ in the cross-correlation and a total reduction of 30 dB to -58.6 dB when using $s_{h_2}(t)$ in the cross-correlation. The ambiguity peaks are now masked by the signal floor for the 8k-mode signals as well. The reduction of the pilots by a factor $(\frac{9}{16})^2$ accounts for the boosted power level of the pilots in both the received signal (reflected targets in a radar system) $s_r(t)$ and the reference LOS signal.

Fig. 14 and Fig. 15 show the auto-correlation of the 2k-mode DVB-T signal and the correlation of the 2k-mode DVB-T signal with the modified reference signal $s_{h_1}(t)$. Fig. 16 shows the cross correlation with the newly proposed modified reference signal $s_{h_2}(t)$. As evident from these figures, for the 2k-mode, the two mis-matched filtering approaches appear

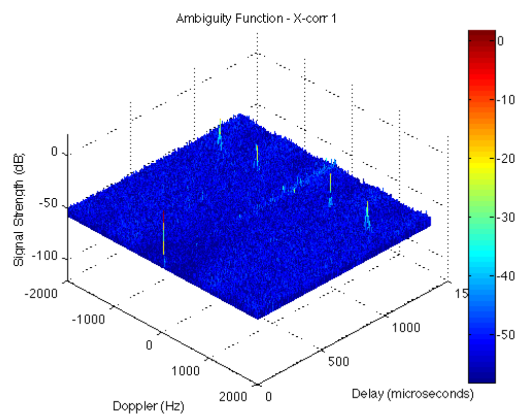

Fig. 12. Cross-correlation of full 8k-mode DVB-T signal with modified reference signal $s_{h_2}(t)$

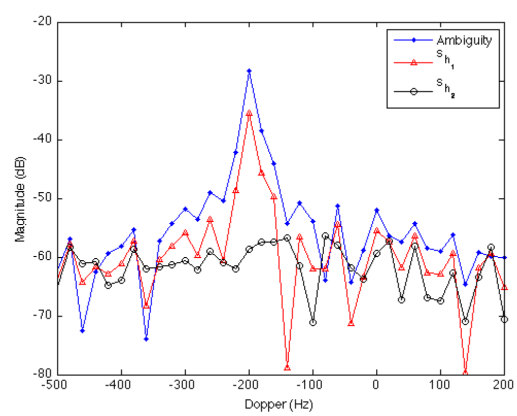

Fig. 13. Comparison of methods for reducing ambiguities of full 8k-mode DVB-T signal: a) Auto-correlation, b) cross-correlation with $s_{h_1}(t)$, c) cross-correlation with $s_{h_2}(t)$

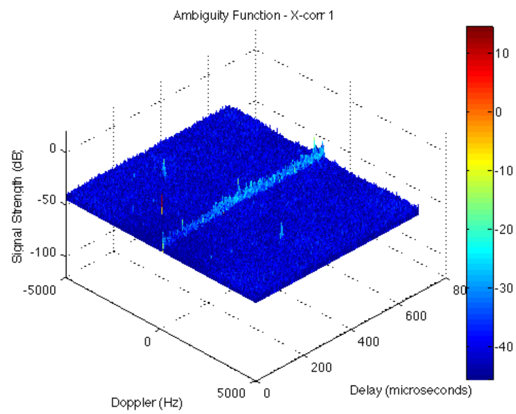

Fig. 14. Auto-correlation of full 2k-mode DVB-T signal

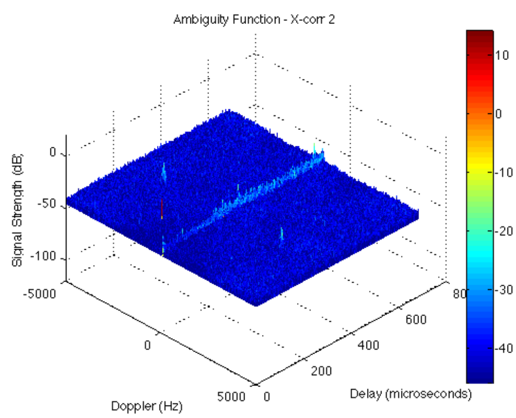

Fig. 15. Cross-correlation of full 2k-mode DVB-T signal with modified reference signal $s_{h_1}(t)$

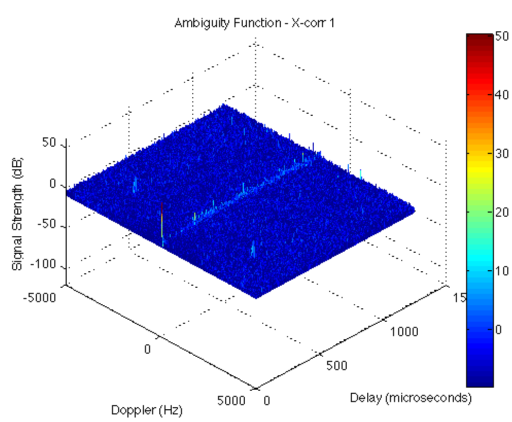

Fig. 16. Cross-correlation of full 2k-mode DVB-T signal with modified reference signal $s_{h_2}(t)$

to give a similar response. The reason for this apparent lack of difference is that the ambiguity peaks are smaller in the 2k-mode signal then in the 8k-mode signal and therefore require less cancellation before they are masked by the signal floor.

V. Conclusion

In conclusion, we have analyzed the use of DVB-T signals in passive radar systems. A DVB-T signal has deterministic components that cause peaks in the ambiguity function at non-zero delay and Doppler offset. These peaks reduce the effectiveness of the radar system as they mask targets at these offsets or contribute to false alarms in the radar system. We offer an analysis of the DVB-T waveform that shows how the deterministic components of the waveform cause these ambiguities. An approach to reducing these peaks is suggested in the literature [4], [5], but while the approach works well for some DVB-T signals (those operating in 2k-mode), the 8k-mode signals do not see as much of a reduction of the ambiguity peaks. We propose an improvement to provide further reduction of the peaks in either mode operation but most importantly in 8k-mode operation.

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