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The impact of channel errors in passive coherent location radar using FM base stations

FM baz istasyonları kullanarak pasif uyumlu konumlandırma radarında kanal hatalarının etkisi

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The Impact of Channel Errors in Passive Coherent Location Radar using FM Base Stations

Highlights

- *Reciprocal filter is used for the pulse compression.*
- *Clutter cancellation is performd by using displaced phase centre antenna (DPCA) approach.*
- *The DPCA performance is analysed for different FM waveforms.*
- *Impact of channel errors is analysed for four different FM waveforms which are lively talk, soft music, dance music, and rock music.*

Graphical Abstract

The impact of channel errors is analysed for an FM based passive bistatic radar system mounted on mobile platforms.

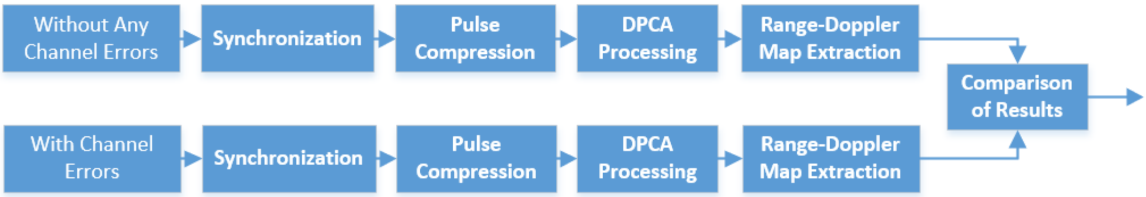

Figure. Flowchart of the proposed

Aim

The aim of this paper is to analyse the impact of channel errors for an FM based passive bistatic radar system mounted on mobile platforms for ground moving target indication (GMTI).

Design & Methodology

The passive radar system which has three antennas is designed. The two of the antennas are for surveillance and the other one is for reference signal. This system which is for gorund moving target indication is placed on mobile platform. Reciprocal filter is used for the pulse compression stage. Clutter cancellation is perfomed by using displaced phase centre antenna (DPCA) approach.

Originality

Impact of channel errors is analysed for four different FM waveforms which are lively talk, soft music, dance music, and rock music. Phase and amplitude differences between receiving channels are studied seperately. Then, it was observed which waveform is more resilient to amplitude and phase mismatches between receiving channels.

Findings

The waveform of lively talk is affected negatively more than the other waveforms and the waveform of rock music is less affected in case of the amplitude mismatches. The waveform of lively talk is affected negatively more than the other waveforms in case of the phase mismatches.

Conclusion

The analysis of the amplitude and phase differences in the received signals of the PCL receiver shows that the performance of the clutter cancellation is significantly degraded. It is clear that the calibration of receiving channels is necessary for the performance of the PCL system.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

FM Baz İstasyonları Kullanarak Pasif Uyumlu Konumlandırma Radarında Kanal Hatalarının Etkisi

Araştırma Makalesi / Research Article

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ÖZ

Bu makale, yeryüzünde hareket halindeki hedeflerin tespiti (YHHT) için seyyar platformlara monte edilmiş FM tabanlı pasif bistatik radar sistemi için kanal hatalarının etkisini göstermektedir. Uyumlu filtreye (UF) kıyasla etkili olan resiprokal filtre, sinyalin zamanla değişen yapısını ortadan kaldırmak için darbe sıkıştırma aşaması için gerçekleştirilir. Kargaşa önleme ve hedef tespiti için faz merkezi kaydırılan anten (FMKA) yöntemi uygulanır. Bu teknik donanım iyi kalibre edilmişse etkilidir. Dolayısıyla alıcı kanallar arasındaki kalibrasyon hatalarının etkileri farklı FM dalga formları için incelenir. Genlik ve faz hatalarının simülasyon sonuçları ayrı ayrı analiz edilir.

Anahtar Kelimeler: Kanal hataları, FMKA, YHHT, pasif radar, resiprokal filtre.

The Impact of Channel Errors in Passive Coherent Location Radar using FM Base Stations

ABSTRACT

This paper presents the impact of channel errors for an FM based passive bistatic radar system mounted on mobile platforms for ground moving target indication (GMTI). Reciprocal filter, which is effective compared to conventional matched filter (MF), is performed for the pulse compression stage to remove the time-variant structure of the signal. The displaced phase centre antenna (DPCA) method is applied for the clutter cancellation and target detection. This technique is effective if the hardware is well calibrated. Thereby, the influences of calibration errors between the receiving channels are studied for different FM waveforms. The simulation results of the amplitude and phase errors are analysed separately.

Keywords: Channel errors, DPCA, GMTI, passive radar, reciprocal filter.

1. INTRODUCTION

Over the past years passive bistatic radar, also known as Passive Coherent Location (PCL), has attracted the attention of publications thanks to the advantages of PCL [1-6]. Unlike active radar, passive radar has various benefits such as low-cost hardware setup, operating covertly, reduced electromagnetic pollution, and operating without any required license. These advantages are derived from the lack of the transmitter. The PCL system operates by using transmitters which already exist in use for other purposes such as Global System for Mobile Communications (GSM) [7], Wireless Fidelity (WIFI) [8], Analogue TV, Digital Audio Broadcast (DAB), Digital Video Broadcasting–Terrestrial (DVB-T) [9, 10], Digital Video Broadcasting–Satellite (DVB-S) [11], and FM radio [12] instead of a dedicated transmitter. On the other hand, the lack of the transmitter in the PCL system causes drawbacks such as complicated signal processing, not having control over the transmitted signal and continuous synchronization between receiver and transmitter.

PCL systems are capable of tracking moving targets, in addition to the detection of target velocity and position. These systems are mounted on stationary and moving platforms. For the PCL system mounted on stationary platforms, target detection and clutter cancellation can be done easily by using filters such as matched filter (MF) or reciprocal filter for pulse compression [13, 14].

Target echos are covered by the sidelobes of clutter echos. This makes the target detection ambiguous and range computation inaccurate. MF does not remove the content of the signal and generates time-variant waveforms. Unlike MF, the reciprocal filter removes the content and generates time-invariant waveforms. Therefore, the reciprocal filter is preferred to remove these side effects.

The PCL system which is mounted on mobile platforms such as airborne and spaceborne radar can be utilized for moving target indication (MTI) [15-19]. Clutter cancellation and target detection on moving platforms are not easy as on the PCL system mounted on stationary platforms. Therefore, the Doppler shift occurs in the frequency of the received signals due to the platform motion and the clutter cancellation cannot be performed perfectly. To overcome this issue, the displaced phase centre antenna (DPCA) technique is used [20, 21]. This technique is a space-time processing concept in radar. It makes the antenna which is mounted on moving platform

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act like stationary in space. Therefore, the downside caused by the platform motion is compensated.

However, the performance of passive radar systems depends on the calibration of channels as well as active radar systems. The amplitude and phase differences between receiving channels may affect negatively the performance of the PCL system, as described in [22]. These differences are due to reasons such as different cable lengths, inequivalent filters, or timing jitter of oscillators in receivers.

The influence of channel calibration issue is analysed for DVB-T based multi-channel PCL system in ground moving target indication (GMTI) [23]. The problem of direct signal interference and clutter cancellation are discussed in [24] for passive radar systems. Different channel calibration strategies are proposed to improve the clutter cancellation performance. Also in [25], the effects of channel errors are evaluated for mobile passive radar system which uses DVB-T as illuminator of opportunity (IO). It is shown that the uncalibrated receiving hardware reduces the performance of the clutter cancellation and moving target detection.

This paper presents the FM based mobile PCL system for GMTI. Firstly, in Section 2, the reference scenario is described and the signal model is obtained. In Section 3, the ambiguities are removed by using reciprocal filter at the pulse compression stage. Then, the application of the DPCA concept is performed in Section 4. Finally, in Section 5, the performance of DPCA is shown for the well calibrated surveillance channels. Besides, the performances of DPCA in the case of existing the amplitude and phase differences between receiving channels are shown, separately. The impacts of inter-channel errors on the clutter cancellation and target detection are studied for different FM waveforms such as lively talk, soft music, dance music, and rock music.

2. SIGNAL MODEL AND REFERENCE SCENARIO

The paper presents a PCL system which is using FM radio signals as a transmitter. The passive radar placed on a mobile platform which has three antennas is considered. The two of the antennas are for surveillance and the other one is for reference signal which is received by the reference antenna (RA). The platform exploits territorial Tx as illuminator of opportunity (IO), which is FM base station.

The surveillance antennas, which are placed with distance d, are mounted in along-track direction and these are referred to as front antenna (FA) and back (BA) antenna. The FA is in front of the platform and the BA is behind the platform, therefore BA occupies the identical spatial position as the FA after T_D time. The platform moves with constant velocity v_P at the constant height HP along the x-axis without changing its direction (see Figure 1).

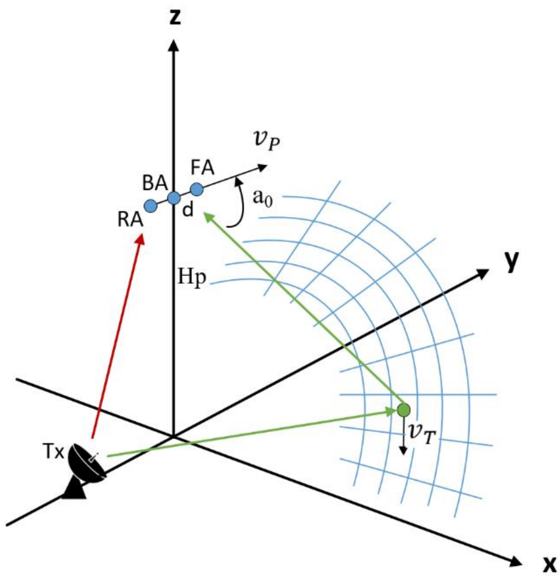


Figure 1. System geometry

The returns from moving objects (target) and stationary objects (clutter) are received by the surveillance antennas and the received signals are characterized as:

$$x^{(n)}(t) = x_C^{(n)}(t) + x_T^{(n)}(t) + x_N^{(n)}(t)\,, \qquad (1)$$

where x_C and x_T define echos from clutters and targets, respectively. x_N represents thermal noise which can be considered as Additive White Gaussian Noise (AWGN) and n refers to the receiving channels (FA and BA).

The returns from target and clutter, which are received by the Rx channels, scattered by point-like scatterers. This echo signal from a single point-like scatterer can be defined as:

$$x_0^{(FA)}(t) = A_0 s(t-\tau_0) e^{j2\pi f_{D_0} t}$$

$$x_0^{(BA)}(t) = A_0 s(t-\tau_0) e^{j2\pi f_{D_0} t} e^{-j2\pi \frac{d}{\lambda}\cos a_0}\,, \qquad (2)$$

where

- A_0 is a complex amplitude which changes according to the antenna gain, scatterer reflectivity, path losses, and transmitted power;
- $s(t)$ is baseband signal transmitted by the Tx;
- τ_0 is the bistatic propagation delay;
- f_{D_0} is the bistatic Doppler shift;
- d is the distance between receiving channels FA and BA;
- λ is the signal carrier wavelength;
- a_0 is the angle between the Rx-scatterer line of sight and the platform velocity vector (direction of the y-axis).

The bistatic Doppler frequency and can be written as:

$$f_{D_0} = \frac{v_P}{\lambda}\cos a_0 - \frac{v_T}{\lambda}\,, \qquad (3)$$

where v_T is bistatic radial velocity derived from the target. This Doppler shift consists of clutter and target contributions. When v_T = 0, Doppler has only the clutter contribution caused by the velocity of the platform.

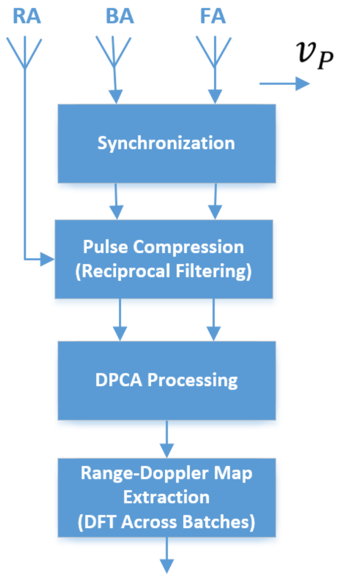


Figure 2. Flowchart of the DPCA approach in the PCL radar system

The methodology to process received signals for FM based PCL is given in Figure 2. The batching design is adopted for the computation of the bistatic range-Doppler map [26, 27]. In this design, the received signals are subdivided into sequential batches after the synchronization stage. The pulse compression is implemented for each batch. The batches are tiered to generate a slow-time/fast-time matrix as shown in Figure 3. By applying discrete Fourier transform (DFT) across the slow-time dimension, the range-Doppler map is obtained.

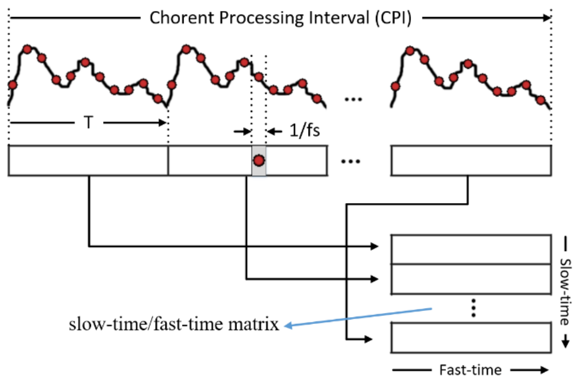


Figure 3. Batching algorithm scheme

For the batching approach, $s(t)$ can be expressed as:

$$s(t) = \sum_{b=0}^{B-1} s_b(t - bT), \qquad (4)$$

where T is the duration of a single batch and B is the number of batches.

Equation (2) can be written in discrete form by sampling with the frequency f_s and defined as follows:

$$x_0^{(FA)}[l] \cong A_0 \sum_{b=0}^{B-1} s_b[l - bL - l_{\tau_0}]\, e^{j2\pi f_{D_0} bT}$$

$$x_0^{(BA)}[l] \cong A_0 \sum_{b=0}^{B-1} s_b[l - bL - l_{\tau_0}]\, e^{j2\pi f_{D_0} bT} e^{-j2\pi \frac{d}{\lambda} \cos a_0}, \qquad (5)$$

where l_{τ_0} is the delay bin corresponding to τ_0. L is the number of samples in each batch and can be calculated as $L = Tf_s$.

$x_C^{(n)}(t)$, $x_T^{(n)}(t)$ and $x_N^{(n)}(t)$ are required to obtain received signals $x^{(n)}(t)$ as seen in Equation (1). $x^{(n)}[l]$, $x_C^{(n)}[l]$, $x_T^{(n)}[l]$ and $x_N^{(n)}[l]$ are discretised version of $x^{(n)}(t)$, $x_C^{(n)}(t)$, $x_T^{(n)}(t)$ and $x_N^{(n)}(t)$ respectively. $x_N^{(n)}[l]$ is presumed as AWGN and $x_T^{(n)}[l]$, which is target contribution, can be calculated by using Equation (5). When calculating the clutter contributions, the returns from all range gates and angles should be considered. Therefore, $x_C^{(n)}[l]$ is obtained as:

$$x_0^{(FA)}[l] \cong A_0 \sum_{b=0}^{B-1} s_b[l - bL - l_{\tau_0}]\, e^{j2\pi f_{D_0} bT}$$

$$x_C^{(BA)}[l] = \sum_{r=1}^{R} \int_{\phi_r} A_r(a) \sum_{b=0}^{B-1} s_b[l - bL - l_{\tau_0}]\, e^{j2\pi \frac{v_P}{\lambda} \cos a bT} e^{-j2\pi \frac{d}{\lambda} \cos a} da, \qquad (6)$$

where R represents the range gates and ϕ_r is the angular sector. The amplitudes $A_r(a)$, which are associated with stationary scatterers, are modelled as the Rayleigh distribution.

3. PULSE COMPRESSION

In active radar systems, the transmitted signal can be controlled due to the reason being that the signal is transmitted by the system itself. Unlike the active radars, passive radar systems do not have their own transmitters and they use external transmitters. For this reason, the waveform of the received signal should be modified by using filters such as MF and reciprocal filter.

The MF generates time-variant responses which means every batch is different from the other one. This causes that the clutter cancellation is not performed efficiently in the DPCA stage which is represented in Section 4.

The reciprocal filter is especially effective compared to MF for clutter cancellation and target detection improvement thanks to the fact that the reciprocal filter makes equal the output of the pulse compression. This allows that the clutter cancellation is performed efficiently in the DPCA stage. Therefore, the reciprocal filter, which generates time-invariant responses, is performed for pulse compression and it produces impeccable input for the DPCA process.

The signal batch changes after the pulse compression as follows:

$$c_b[l] = s_b[l - bL] * h_b[l] = kL\delta[l]\,, \tag{7}$$

where '*' is the convolution operator and k is a multiplicative constant. $h_b[l]$ is the reciprocal filter which is defined as:

$$h_b[l] = kIDFT\{s_b[m]^{-1}\}\,, \tag{8}$$

where $s_b[m]$ is DFT of $s_b[l]$.

The convolution in the time domain corresponds to multiplication in the frequency domain. Using this principle, to perform the convolution processing in Equation 7, the DFTs of both sides are taken separately. Then, the elementwise multiplication of these DFTs is performed. Finally, inverse discrete Fourier transform (IDFT) of the result is taken.

$c_b[l]$ becomes time-invariant for each batch thanks to the reciprocal filter. Therefore, the echo signal can be obtained as a fast-time/slow-time data matrix by using the output of pulse compression ($c_b[l]$) in Equation 5:

$$f_0^{(FA)}[l,b] = A_0 c_b[l - l_{\tau_0}]e^{j2\pi f_{D_0} bT}$$

$$f_0^{(BA)}[l,b] = A_0 c_b[l - l_{\tau_0}]e^{j2\pi f_{D_0} bT}e^{-j2\pi\frac{d}{\lambda}\cos a_0}\,. \tag{9}$$

4. CONCEPT OF DPCA

The DPCA approach is a method for suppressing the clutter effects which are especially caused by the platform motion in passive GMTI [28, 29]. These clutter effects influence the target detection negatively.

As shown in Figure 4, the DPCA approach is based on the subtraction of the received echos by two surveillance antennas (mounted in side-looking condition) whose phase centres take the positions of each other at different points of time. The surveillance antennas are displaced by d along the direction of the platform movement. The pulse repetition frequency (PRF) is adjusted for the perfect DPCA condition [20, 30] so that the phase centre of BA should occupy at the same spatial position of the phase centre of FA after an integer number K ($K =$ PRF. d/v_P) of pulse repetition intervals (PRI).

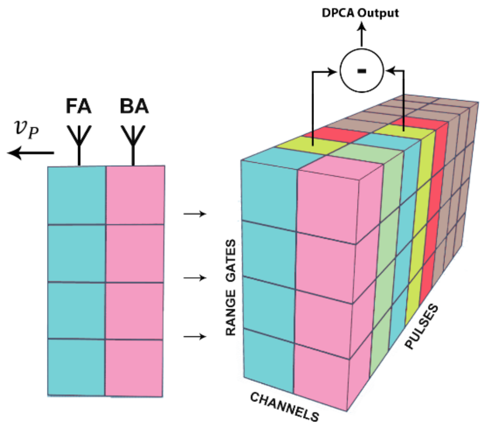


Figure 4. Batching algorithm scheme

The echos received at the same phase centre by FA and BA are subtracted to perform successful clutter cancellation. The output of the DPCA process is obtained as:

$$y_0[l,b] = f_0^{(BA)}[l,b] - f_0^{(FA)}[l,b-K]\,. \tag{10}$$

The DFT is performed to $y_0[l,b]$ across slow-time dimension to obtain the range-Doppler map of the single point-like scatterer which is written as follows:

$$z_0[l,m] = \sum_{b=0}^{B-1} y_0[l,b]e^{-j2\pi\frac{m}{BT}bT}$$

$$= A_0 e^{-j2\pi\frac{v_P}{\lambda}\cos a_0 KT}\sum_{b=0}^{B-1} e^{j2\pi(f_{D_0}-\frac{m}{BT})bT}\Big[c_b[l - l_{\tau_0}] - e^{j2\pi\frac{v_T}{\lambda}KT}c_b[l - l_{\tau_0}]\Big]\,. \tag{11}$$

The range-Doppler map of the clutter, which contains contributions of all range gates, can be obtained as:

$$z_c[l,m] = \sum_{r=1}^{R}\int_{\phi_c} A_c(a)e^{-j2\pi\frac{v_P}{\lambda}\cos aKT}\sum_{b=0}^{B-1}\big(c_b[l - l_{\tau_r}] - c_{b-K}[l, l_{\tau_r}]\big)e^{j2\pi(\frac{v_P}{\lambda}\cos a - \frac{m}{BT})bT}\,da\,. \tag{12}$$

The evaluation of the performance of DPCA target detection and clutter cancellation can be expressed by the improvement factor (IF). The IF can be defined as:

$$IF = IA * TG = \frac{I_{in}}{I_{out}} * \frac{T_{out}}{T_{in}}\,, \tag{13}$$

where IA and TG represent interference attenuation and target gain, respectively. IA has a thermal contribution in addition to the clutter contribution. I_{in} and T_{in} are interference power and target signal power before DPCA. I_{out} and T_{out} are interference power and target signal power after DPCA, respectively. These values (I_{in}, T_{in}, I_{out}, and T_{out}) are calculated by taking the average of many results.

5. RESULTS AND DISCUSSION

The surveillance antennas of the PCL system, which are FA and BA, should be well calibrated for the performance of the DCPA processing.

The results obtained with the reciprocal filter in case of the well calibrated surveillance antennas are shown in Figure 5. Figure 5a and Figure 5b show the range-Doppler maps before DPCA processing and after DPCA processing, respectively.

5.1. Simulation Parameters

A simulation of the PCL system which is based on FM radio transmitter was performed by using MATLAB. The carrier frequency (f_c) was set to 100 MHz and the wavelength (λ) was 3 m. The angular sector (ϕ_r) was interval [0, π]. The number of the range gates and the clutter patches were set to 100 and 30 respectively, which led to each clutter patch has a width of δ_φ= 6°. The received signal was sampled with a sampling frequency (f_s) of 200 kHz. The number of batches in each coherent processing interval (CPI) was 93 and the duration of each batch (PRI) was 0.5 ms. The velocity of the platform (v_P) was set to 500 m/s. The distance between surveillance antennas (d), which should be less than λ/2=1.5 m, was set to 0.5 m to fulfil the DPCA condition. The power level of clutter was scaled up in amplitude by taking account of clutter-to-noise ratio (CNR) 40 dB after the signal generated by using Equation 6.

As seen in Figure 5a, strong clutter echos appear in all the range gates at Doppler interval [-166 Hz, 166 Hz]. This interval value depends on the velocity of the platform and wavelength of the transmitted signal. The strong clutter contributions cause negatively the detection of slowly moving targets whose Doppler shift is smaller than the v_P/λ.

The DPCA has effectively removed the clutter contributions as in Figure 5b. Also, the main clutter ridge has been eliminated perfectly. This makes the detection of slowly moving targets possible. Still, residuals exist across the whole range-Doppler map because of border effects at the pulse compression stage. These residuals are below thermal noise in practice and negligible. As clearly seen, the DPCA processing with reciprocal filter provides perfect clutter cancellation.

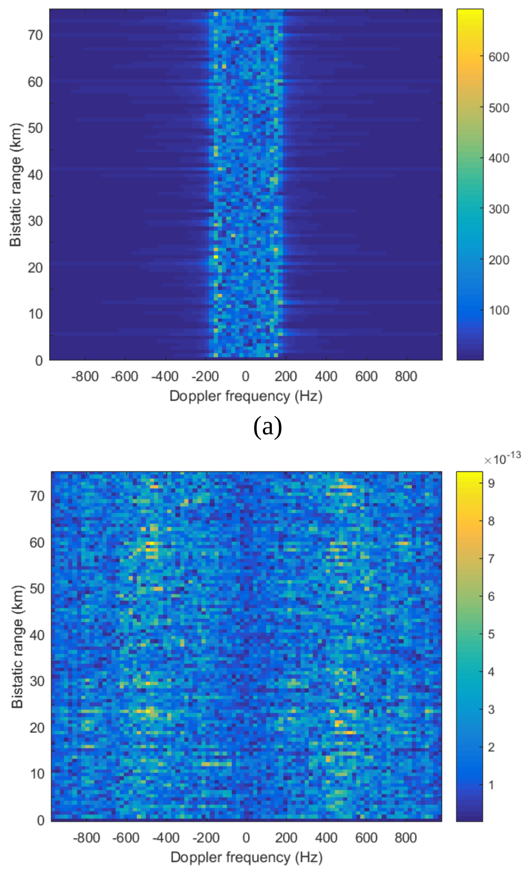


Figure 5. Range-Doppler maps (in dB) for the reciprocal filter including clutter echos only: (a) before DPCA processing; (b) after DPCA processing

Moreover, the proposed method is applied for evaluating the performance of DPCA processing by using four different FM radio waveforms such as lively talk, soft music, dance music, and rock music. As seen in Figure 6, the performance of DPCA processing varies due to waveform instability. Therefore, the performance is lower compared to active radar with stable waveform. Nevertheless, the DPCA approach is feasible for airborne passive radar in GMTI applications.

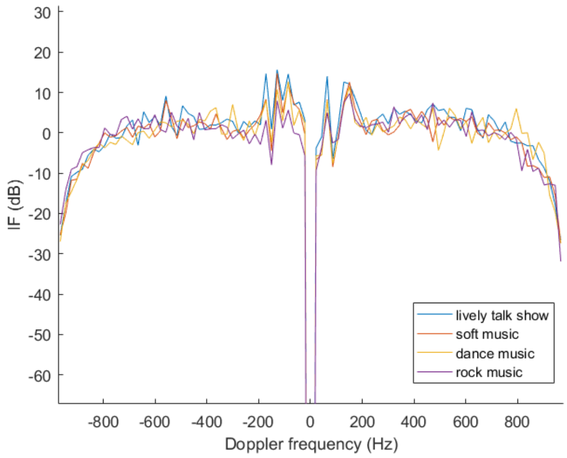


Figure 6. IF with respect to Doppler frequency of different waveforms

However, there may be inter-channel errors between each surveillance antenna due to reasons such as inequivalent filters, different cable lengths, or timing jitter of oscillators in receivers [30, 31]. These inter-channel errors are the differences in amplification ε_A and phase ε_φ.

5.2. Results of Inter-Channel Errors

To analyse the impact of the inter-channel errors, one of the received signals is modelled by using $s(t)$ and the other one by using $s_E(t)$ which is given below.

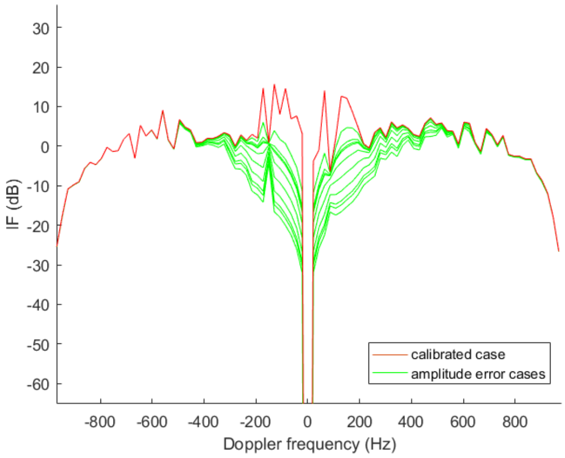
$$s_E(t) = \varepsilon_A s(t) e^{j\varepsilon_\varphi} \qquad (14)$$

The two error sources ε_A and ε_φ were analysed independently to observe their influences. They were calculated as a probability density function of the relevant error (i.e. the errors were considered as random variables). The implementation of errors was repeated ten times and their IFs were calculated to analyse the impact of inter-channel errors for four different FM waveforms.

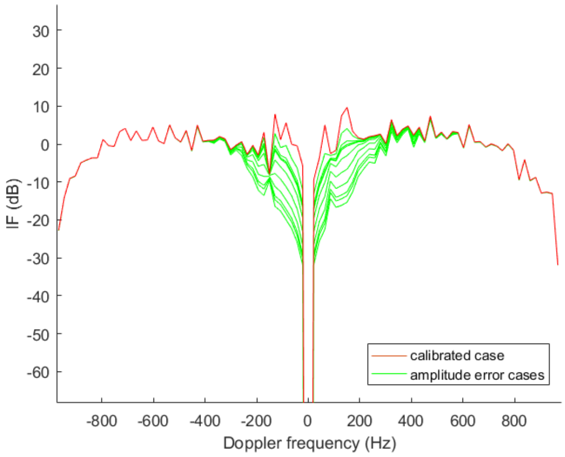
5.2.1. Impact of amplitude inequalities

The amplitude disparities were analysed. The amplitude error values were modelled as normal distributed random variables with mean value of μ=1 and a variance σ_A^2= 0.4.

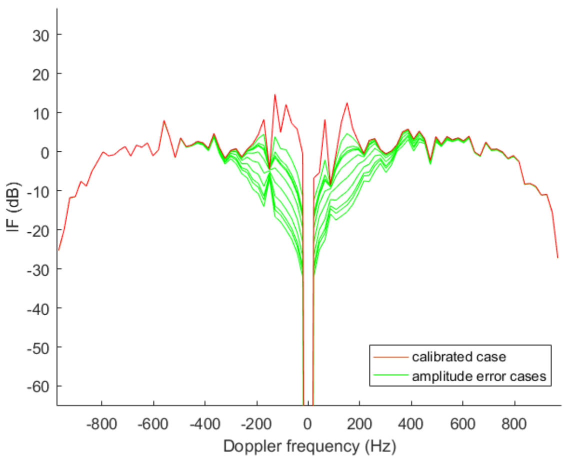
Both IF of the amplitude error cases and the errorless case (calibrated case) for four different FM waveforms are shown in Figure 7. The errors are indicated with the green lines and the calibrated case is indicated with the red line. As seen clearly, the IF gets worse and the notch widening by comparison with the calibrated case. In short, the inter-channel amplitude differences diminish the performance of clutter suppression.



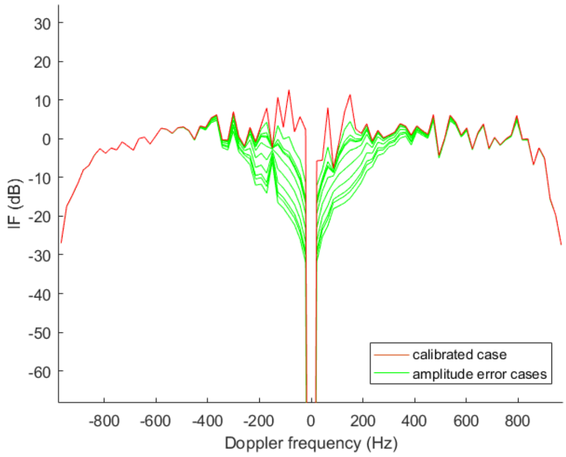
(a)



(b)



(c)



(d)

Figure 7. IF with and without the impact of amplitude errors for different FM waveforms such as: (a) lively talk; (b) soft music; (c) dance music; (d) rock music

Moreover, the effects of amplitude error of different FM waveforms were compared as seen in Figure 8. Mean of ten different IFs which are shown in Figure 7 was obtained for each waveform. Subtracting the calibrated case IF and obtained mean IF (error case), it was observed which waveform is more resilient to amplitude mismatches between receiving channels. While the waveform of lively talk is affected more than the other waveforms and the waveform of rock music is less affected (see Figure 8).

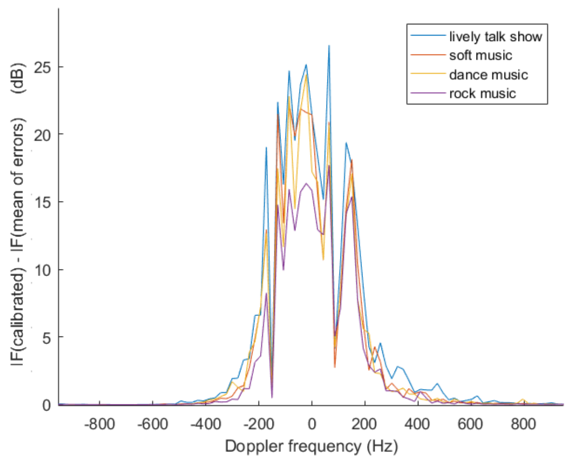
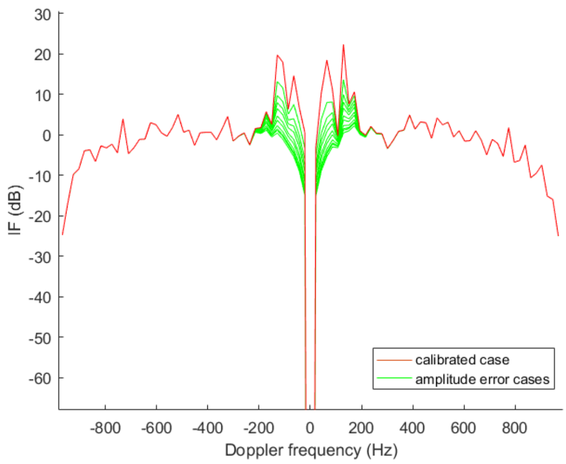


Figure 8. The comparison of amplitude error for various FM waveforms

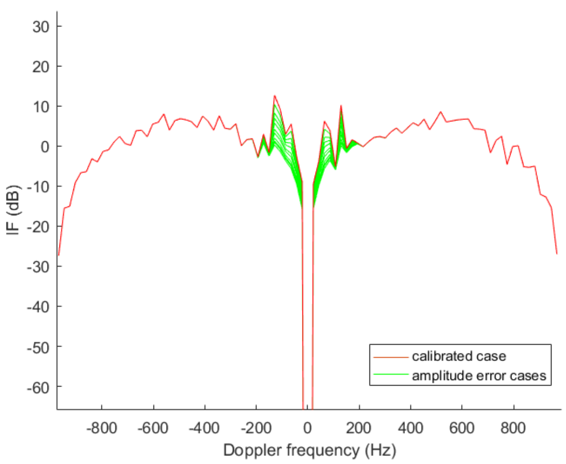
5.2.2. Impact of phase inequalities

The phase errors were modelled as being uniformly distributed from $-\pi/4$ to $+\pi/4$.

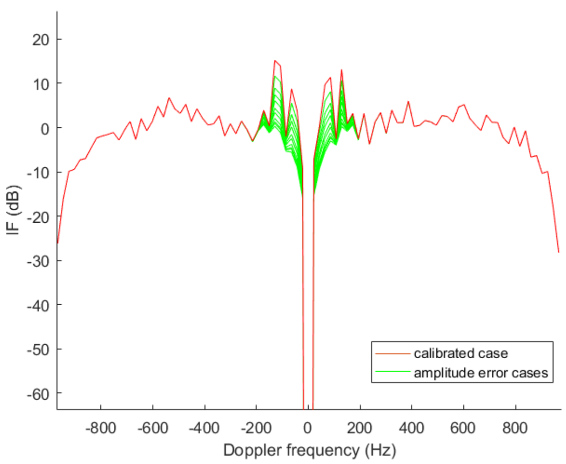
The IF of the phase error cases and the errorless case for four different FM waveforms are shown in Figure 9. The red line indicates the errorless case (calibrated case), while the green lines represent the phase error cases. The phase errors have a negative impact on clutter suppression but not as much as amplitude errors. Additionally, the notch widening is not as broad as that caused by the amplitude mismatches. Still, the phase error remarkably reduces the performance of the clutter suppression, which makes target detection difficult.



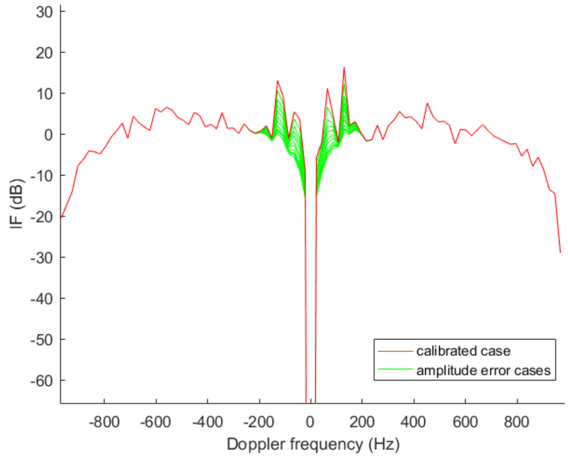
(a)



(b)



(c)



(d)

Figure 9. IF with and without the impact of phase errors for different FM waveforms such as: (a) lively talk; (b) soft music; (c) dance music; (d) rock music

Besides, the effects of phase error of different FM waveforms were compared as seen in Figure 10. Mean of ten different IFs which are shown in Figure 9 was calculated for each waveform. The calibrated case IF and calculated mean IF (error case) were subtracted for evaluating which waveform is more resilient to phase mismatches between receiving channels. As seen in Figure 10, the waveform of lively talk is affected more than the other waveforms.

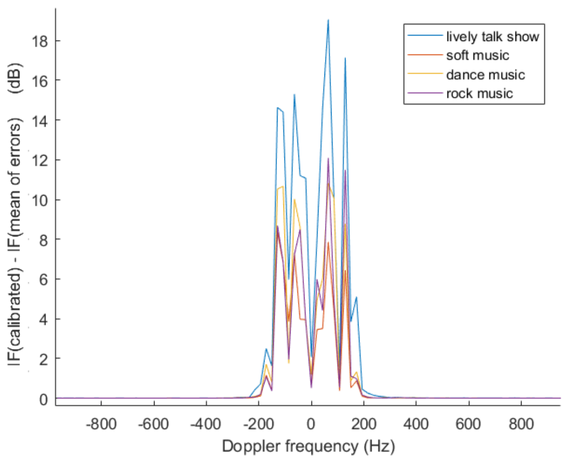


Figure 10. The comparison of phase error for various FM waveforms

6. CONCLUSION

The FM based PCL system has been considered for the clutter cancellation in GMTI. The ambiguities have eliminated by applying reciprocal filter at a pulse compression stage thanks to the ability of removing the content of the received signal which makes the signal time-invariant. The DPCA approach is used for the clutter cancellation of the PCL system.

Also, it has been provided simulations for the uncalibrated state of the channels. Thereby, the effects of the calibration errors on the DPCA processing has been discussed for four different FM radio waveforms. The analysis of the amplitude and phase differences in the received signals of the PCL receiver shows that the performance of the clutter cancellation is significantly degraded. It is clear that the calibration of receiving channels is necessary for the performance of the PCL system.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Kadir İLERİ: Performed the experiments and analyse the results.

Necmi Serkan TEZEL: Performed the experiments and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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