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Nonstationary Interference Excision for Noise Radar Systems using Time-Frequency based Methods

T. Thayaparan, M. Dakovic and L. Stankovic

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Abstract

The problem addressed in this memorandum is nonstationary interference suppression in noise radar systems. Towards this aim, linear time-frequency (TF) transforms, short time Fourier transform (STFT) and local polynomial Fourier transform (LPFT) are used as a means of signal representation. The noise radar return signal is a wideband random signal occupying the whole TF plane, while the interference signal is well concentrated in the TF plane. This implies that the filtering of the received signal can be performed by using a binary mask to excise only a portion of the TF plane corrupted by the interference. Simulations carried out on the radar return signal corrupted by an extremely strong nonstationary interferences, covering the same time and frequency ranges. Results confirm the effectiveness of the proposed method.

Résumé

Le présent document aborde le problème de la suppression du brouillage non stationnaire dans les systèmes radar à onde de bruit. Dans ce contexte, des transformées linéaires temps-fréquence (TF), des transformées de Fourier fenêtrées (STFT) et des transformées de Fourier polynomiales locales (LPFT) sont utilisées pour représenter les signaux. L'écho du radar à onde de bruit est constitué d'un signal aléatoire à large bande occupant tout le plan TF, alors que le signal de brouillage est bien concentré dans le plan TF. Le filtrage du signal reçu peut ainsi être effectué à l'aide d'un masque binaire qui extrait seulement une partie du plan TF corrompu par le brouillage. Des simulations ont été effectuées au moyen d'un écho radar corrompu par du brouillage non stationnaire extrêmement intense, couvrant les mêmes plages de temps et de fréquence. Les résultats ont confirmé l'efficacité de la méthode proposée.

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Executive summary

Nonstationary Interference Excision for Noise Radar Systems using Time-Frequency based Methods

T. Thayaparan, M. Dakovic, L. Stankovic; DRDC Ottawa TM 2007-334; Defence R&D Canada – Ottawa; December 2007.

Background: Effective battlefield radar surveillance and protection of the nation's borders, harbours, air space, and marine assets require covert and interference-free operation. This includes not only that friendly radar signals be undetected by the enemy, but also that such systems be immune from jamming and external electromagnetic interference (EMI). While many low probability of intercept (LPI) and low probability of detection (LPD) waveforms have been developed and tested over the past years, these primarily rely upon the use of pseudorandom transmit waveforms. However, with the increasing storage and computational capabilities of advanced digital signal processors, it has become easier for the intelligent adversary not only to detect, characterize, and recognize such signals, but also to use the information to jam and confuse friendly radar systems. Random noise radar is an attractive and viable option for use in these applications.

Random noise radar refers to techniques and applications that use incoherent noise as the probing transmit waveform. One of the major advantages of using noise as the transmit signal is its inherent immunity from detection, unintended interference, and hostile jamming.

Results: The problem addressed in this memorandum is nonstationary interference suppression in noise radar systems. Towards this aim, linear time-frequency (TF) transforms, short time Fourier transform (STFT) and local polynomial Fourier transform (LPFT) are used as a means of signal representation. The noise radar return signal is a wideband random signal occupying the whole TF plane, while the interference signal is well concentrated in the TF plane. This implies that the filtering of the received signal can be performed by using a binary mask to excise only a portion of the TF plane corrupted by the interference. Simulations carried out on the radar return signal corrupted by an extremely strong nonstationary interference sources, covering the same time and frequency ranges. Results confirm the utility of the proposed method.

Significance: Results clearly demonstrate that the time-frequency based interference suppression method can significantly improve the detection performance of the noise radar systems in extremely strong nonstationary interference environments. This interference suppression method can potentially be extended to other relevant applications such as over-the-horizon radar systems (OTHR), through-wall imaging

systems, phased array radar systems, global positioning satellite (GPS) receivers, global navigation satellite systems (GNSSs), etc. Another important application of this method is jammer rejection in the spread spectrum (SS) communication systems. Different methods have been proposed for rejection or mitigation of interferences of this kind, in order to improve interference immunity of SS systems and provide more reliable receiving and decoding of the useful signal. The proposed method presents another viable approach to jammer mitigation and enhances the performance of the SS receiver in such severe interfering environment. The proposed method may also be extended to the case of multiple jammers. This method can generally be applied whenever the desired signal is corrupted by broadband interferences characterized by narrowband instantaneous bandwidths.

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Nonstationary Interference Excision for Noise Radar Systems using Time-Frequency based Methods

T. Thayaparan, M. Dakovic, L. Stankovic; DRDC Ottawa TM 2007-334; R & D pour la défense Canada – Ottawa; décembre 2007.

Contexte : Afin de surveiller et de protéger efficacement les frontières, les ports, l'espace aérien et les ressources maritimes d'un pays, un radar de champ de bataille doit pouvoir fonctionner furtivement et sans brouillage. Il est donc non seulement nécessaire que l'ennemi ne puisse pas détecter les signaux du radar ami, mais aussi que le système soit protégé contre l'interférence et le brouillage électromagnétique externe. Bien qu'un grand nombre de formes d'onde à faible probabilité d'interception (LPI) et faible probabilité de détection (LPD) aient été établies et mises à l'essai au cours des dernières années, elles se fondent principalement sur des formes d'onde à émission pseudo-aléatoire. L'accroissement des ressources de stockage et de calcul des processeurs de signaux numériques perfectionnés facilite toutefois la tâche de l'adversaire intelligent qui veut non seulement détecter, caractériser et reconnaître les signaux transmis, mais aussi utiliser l'information pour brouiller et perturber les systèmes radar amis. Le radar à onde de bruit aléatoire constitue une solution attrayante et viable pour ces applications.

Le radar à onde de bruit aléatoire fait appel à des techniques et applications utilisant le bruit incohérent comme forme d'onde d'exploration et de transmission. L'un des principaux avantages de ce mode de fonctionnement tient à l'immunité inhérente à la détection, au brouillage involontaire et à l'interférence ennemie.

Résultats : Le présent document aborde le problème de la suppression du brouillage non stationnaire dans les systèmes radar à onde de bruit. Dans ce contexte, des transformées linéaires temps-fréquence (TF), des transformées de Fourier fenêtrées (STFT) et des transformées de Fourier polynomiales locales (LPFT) sont utilisées pour représenter les signaux. L'écho du radar à onde de bruit est constitué d'un signal aléatoire à large bande occupant tout le plan TF, alors que le signal de brouillage est bien concentré dans le plan TF. Le filtrage du signal reçu peut ainsi être effectué à l'aide d'un masque binaire qui extrait seulement une partie du plan TF corrompu par le brouillage. Des simulations ont été effectuées au moyen d'un écho radar corrompu par des sources de brouillage non stationnaire extrêmement intense, couvrant les mêmes plages de temps et de fréquence. Les résultats ont confirmé l'efficacité de la méthode proposée.

Portée : Les résultats démontrent clairement que la méthode temps-fréquence de suppression du brouillage peut améliorer considérablement le rendement de détec-

tion des systèmes radar à onde de bruit dans des conditions de brouillage non stationnaire extrêmement intense. Cette méthode de suppression du brouillage pourrait éventuellement être adaptée à d'autres applications pertinentes, comme les systèmes radar transhorizon (OTHR), au moyen de systèmes d'imagerie à travers les murs, de systèmes radar à commande de phase, de récepteurs du système de positionnement à couverture mondiale (GPS), de systèmes mondiaux de navigation par satellite (GNSS), etc. Cette méthode trouve une autre application importante dans le rejet du brouillage à l'intérieur des systèmes de communications à spectre étalé (SS). Différentes méthodes ont été proposées pour le rejet ou l'atténuation du brouillage de ce type, de manière à améliorer l'immunité au brouillage des systèmes SS et à permettre la réception et le décodage plus fiables du signal utile. La méthode proposée présente une autre solution viable à l'atténuation du brouillage et améliore le rendement du récepteur SS dans des conditions de brouillage intense. Elle peut aussi s'adapter au cas de brouillage multiple. Cette méthode peut généralement s'appliquer chaque fois que le signal utile est corrompu par du brouillage à large bande constitué de bandes instantanées étroites.

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1 Introduction

The term "random noise" as applied to radar refers to techniques and applications that use incoherent noise as the probing transmit waveform. Because of the truly random transmitting signal, noise radars have many advantages over conventional radars, including unambiguous estimation of both range and velocity, high immunity to noise, low probability of intercept (LPI), high electromagnetic compatibility, good electronic counter countermeasure (ECCM) capability, good counter electronic support measure (CESM) capability, and ideal thumbtack ambiguity function [1]-[12].

Over the past few years, the research has been devoted to the development and implementation of random noise radar by various research groups [4], [7], [8], [9]. Recent research has investigated the potential use of noise radar for ultrawideband SAR/ISAR imaging, Doppler and polarimetric measurements, collision warning, detection of buried objects, and targets obscured by foliage [2], [5], [8]-[12]. Wide bandwidth provides high range resolution, and an extended pulse length reduces peak power. The non-periodic waveform suppresses the range ambiguity while reducing both the probability of intercept and interference.

Mutual interference and low probability of interception capabilities of noise radar were evaluated in previous studies. The results show that noise radars are unlikely to interfere with other noise radar systems or other radar systems in the same band. It is also shown that in a variety of noisy environments, the noise radar has a much lower LPI than the conventional LFM radar. The noise radar's exceptional performance in the above evaluations indicates that it is a suitable radar system for a variety of applications frequently improving upon the performance of conventional systems [13], [14].

In this memorandum we have studied the influence of an extremely strong deterministic broad-band interference (signal to interference ratio as low as -40dB), covering the frequency and time ranges of the operating noise radar. A time-frequency (TF) based interference suppression technique is developed and is based on the property of time-frequency representations to localize signals in the TF plane. Two TF transforms, the short time Fourier transform (STFT) and the local polynomial Fourier transform (LPFT), are used. More precisely, time-varying filters based on the STFT and LPFT are developed. Since the random noise radar signal occupies the whole TF plane, while the interference signal is a broadband signal characterized with a narrow instantaneous bandwidth, the time-varying filtering is performed, via binary mask, which removes the interference's TF signature without significant degradation of the radar return signal. Moreover, the LPFT based receiver outperforms the STFT based receiver since it optimally concentrates an interference source in the TF plane. In numerical illustrations we have considered two types of interferences: a broad-band sinusoidally modulated signal and a linearly frequency modulated (LFM) signal, corresponding to a strong interfering LFM radar, which covers the same time and frequency ranges as the operating noise radar.

The theoretical background, including the STFT, the LPFT, time varying filtering, and correlation-based noise radar principles, is given in Section 2. Section 3 introduces two methods for binary mask implementation. The proposed TF filtering methods' performances are evaluated by means of numerical examples in Section 4. It has been shown that the noise radar performs in a satisfactory way, even with very strong nonstationary broadband interference.

2 Theoretical background

In this section, a short introduction to linear TF methods, i.e., STFT and LPFT, is given. Furthermore, the section also provides a brief description of time-varying filtering and correlation based noise radar principles.

The baseband received signal $r(n)$ comprises three sequences as follows:

$$r\left(n\right)=x\left(n\right)+I\left(n\right)+\xi\left(n\right) \tag{1}$$

where $x(n)$ is a noise radar signal sequence (complex white Gaussian noise sequence with zero mean and variance σ_x^2), $I(n)$ is an interference signal sequence and $\xi(n)$ is a complex additive white Gaussian noise (AWGN) sequence, with zero mean and variance σ_ξ^2 uncorrelated with $x(n)$. The interference is assumed to be a nonstationary signal characterized by a narrowband instantaneous bandwidth and by the following expression:

$$I\left(n\right)=A_I e^{j\varphi_I(n)}$$

where $\varphi_I(n)$ is the phase and A_I is the magnitude of the interference.

Signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) are defined in the following way:

$$\begin{aligned} SNR &= 20\log_{10}\frac{\sigma_x}{\sigma_\xi} && (2)\\ SIR &= 20\log_{10}\frac{\sigma_x}{A_I}. && (3) \end{aligned}$$

The influence of the interference signal on the desired radar signal can be mitigated by using TF methods. Herein, we are interested only in linear TF methods, that allow the perfect reconstruction (synthesis) of the observed signal. Two such methods, i.e., short-time Fourier transform and local polynomial Fourier transform, will be used as a means of interference suppression in this memorandum.

2.1 Short-time Fourier transform

The STFT of the signal $r\left(n\right)$ [16], denoted as $STFT_r\left(n,k\right)$, is obtained by sliding the window function $w(m)$ over the signal $r\left(n\right)$ and implementing the DFT on the product of $r\left(n\right)$ and window at the current position, i.e.,

$$\begin{aligned} STFT_r\left(n,k\right) &= \sum_{m=-N/2}^{N/2-1} r\left(n+m\right)w\left(m\right)e^{-j\frac{2\pi}{N}mk}\\ &= DFT\left[r\left(n+m\right)w\left(m\right)\right] && (4) \end{aligned}$$

where N is the number of frequency bins adopted in the DFT calculation. The window function is usually real and symmetric with the property that $w(0) = 1$. A simple manipulation of (4) gives the STFT synthesis equation

$$r(n) = \frac{1}{N} \sum_{k=0}^{N-1} STFT_r(n,k). \tag{5}$$

This relation states that the signal $r(n)$ can be obtained by summing its STFT values over the frequency variable for the fixed instant n.

2.2 Local polynomial Fourier transform

The LPFT has been recently introduced in the TF analysis [17], [18], with the Mth order discrete form of the LPFT of the sequence $r(n)$ being defined as

$$\begin{aligned} LPFT_r^M(n,k) &= \sum_{m=-N/2}^{N/2-1} r(n+m) w(m)\, e^{-j \sum\limits_{i=1}^{M} \omega_i \frac{m^{i+1}}{(i+1)!}} e^{-j\frac{2\pi}{N}mk} \\ &= DFT\left(r(n+m) w(m)\, e^{-j \sum\limits_{i=1}^{M} \omega_i \frac{m^{i+1}}{(i+1)!}} \right) \end{aligned} \tag{6}$$

where $w(m)$ and N are the same as in the STFT definition and ω_i is the ith transform parameter. The relation (6) indicates that the LPFT of the received signal can be calculated analogously to the STFT, i.e., by sliding the analysis window $w(m)$ over the modulated received signal

$$r(n+m) e^{-j \sum\limits_{i=1}^{M} \omega_i \frac{m^{i+1}}{(i+1)!}}$$

and implementing the DFT on the product of the modulated signal and window at the current position.

The LPFT parameters ω_i for $i = 1, 2, ..., M$ are calculated so as to optimally concentrate the signal (i.e., interference in this case) in the TF plane for a given analysis window. Towards this goal, an order adaptive algorithm is developed in [17] and it is shown to keep calculation complexity at a relatively low level. Furthermore, it is shown that the second-order LPFT produces results almost independent of the parameters of FM interference sources, thus preventing the need for a time-consuming calculation of the higher-order LPFT.

2.3 Time-varying filtering: Binary mask

The spectrum of the noise radar signal is flat, while the interference signal occupies a narrow frequency band at each time instant. The time-varying filtering described in [15] can be easily implemented here. The interference excision is performed in the TF plane by removing its TF signature through a time-varying filter. This filter can be implemented as a binary mask, denoted as **B**, which is a function defined in the following way:

$$B(n,k) = \begin{cases} 0, & \text{interference exists in } (n,k) \\ 1, & \text{otherwise.} \end{cases} \tag{7}$$

Practically, $B(n,k)$ will equal 1 only for points (n,k) of the TF plane where an interference power can be neglected.

The synthesis is performed on the masked transform to recover the "jammer-free" received signal $r'(n)$ as follows:

$$r'(n) = \frac{1}{N}\sum_{k=0}^{N-1} STFT_r(n,k)B(n,k) \tag{8}$$

or

$$r'(n) = \frac{1}{N}\sum_{k=0}^{N-1} LPFT_r^M(n,k)B(n,k)\,. \tag{9}$$

2.4 Correlation Receiver

The correlation receiver uses the principle that when the reference signal, delayed by T_{ref}, is correlated with the actual target echo, the peak value of the correlation function indicates the distance to the target (the amount of time delay of the reference signal is also a measure of distance to the target), while Doppler filters, following the correlator,l output target velocity [7]. In this method, the return signal from the target is cross-correlated with a time-delayed replica of the transmit waveform. When T_{ref} is varied a strong correlation peak is obtained for $T_{ref} = T_0$, which gives an estimate of the target range $r_0 = cT_0/2$.

Let us consider a radar emitting a time-limited signal $x(t)$. Denote the received signal by $y(t)$. Furthermore, we assume that a single point scatterer is located at the range r_0 along the radar line-of-sight (LOS). From this assumption, the received signal can be written as:

$$y(t) = A_\sigma x(t - T_0) + \varepsilon(t) \tag{10}$$

where $T_0 = 2r_0/c$ is the round-trip delay caused by the finite speed of the electromagnetic waves, $\varepsilon(t)$ is an undesired part of the received signal (noise caused by the reflection from other objects along the LOS and possible jamming signals) with A_σ denoting target reflectivity. Without loss of generality we will assume that $A_\sigma = 1$. The correlation of the emitted and received signal can be written as:

$$R(\tau) = \int_0^{T_{int}} y(t)x^*(t-\tau)dt. \tag{11}$$

where T_{int} is the integration time. In the noiseless case, the maximum value of $|R(\tau)|$ occurs at the point $\tau = T_0$.

Let us now assume that $x(t)$ is a white stationary Gaussian random process with autocorrelation function $R_{xx}(\tau)$. The output of the correlation receiver given by (11) is also a random process. Let us analyze the expected value of (11) as:

$$\begin{aligned} E[R(\tau)] &= E[\int_0^{T_{int}} y(t)x^*(t-\tau)dt] \\ &= \int_0^{T_{int}} E[y(t)x^*(t-\tau)]dt \\ &= \int_0^{T_{int}} E[x(t-T_0)x^*(t-\tau)] + E[\varepsilon(t)x^*(t-\tau)]dt \\ &= \int_0^{T_{int}} R_{xx}(\tau - T_0)dt + \int_0^{T_{int}} E[\varepsilon(t)x^*(t-\tau)]dt \end{aligned} \tag{12}$$

If the emitted signal $x(t)$ and the noise $\varepsilon(t)$ are independent processes then the second term in (12) is equal to zero and we get:

$$E[R(\tau)] = T_{int}R_{xx}(\tau - T_0). \tag{13}$$

Since the autocorrelation function's maximum occurs at $u = 0$ ($R(\tau) \leq R(0)$), the delay T_0 can be estimated as the position of the maximum. Thus:

$$T_0 = \max_{\tau} |E[R(\tau)]| \tag{14}$$

Special cases:

- Let $x(t)$ be the white stationary Gaussian random process. The autocorrelation function is $R_{xx}(\tau) = I_0\delta(t-\tau)$. This is an ideal shape since $E[R(\tau)] = T_{int}I_0\delta(t-\tau)$, and its maxima are well defined (only one point is different from zero). Note that signals of this form are not bandlimited and they can not be used in practical applications.
- Let $x(t)$ be the bandlimited white stationary Gaussian random process with power spectral density (PSD) $S_{xx}(f) = S_0$ for $f_0 - B/2 \leq f < f_0 + B/2$ and $S_{xx}(f) = 0$ otherwise. The autocorrelation function is of the form:

  $$R_{xx}(\tau) = S_0 e^{j2\pi f_0 \tau} \frac{\sin(\pi B \tau)}{\pi \tau} \tag{15}$$

  with well a defined maximum at $\tau = 0$, and with a first side lobe that is $B\frac{\pi}{2}$ times lower than the main lobe.

3 Binary mask implementation

This section offers two methods of binary filtering mask implementation and, through numerical examples, assess their performances, both in the STFT and LPFT case. In all examples presented in this section, the length of the received sequence is $L = 2048$, $N = 256$ and $SNR = 0$ dB. The interference is assumed to be a sinusoidal FM signal characterized by $SIR = -20$ dB. In the LPFT calculation, the perfect knowledge of the LPFT parameters is assumed. Furthermore, only the first and second order LPFT will be herein considered.

In order to assess performances of the proposed filtering methods, i.e., to estimate a remaining interference power compared to a remaining radar signal power after a binary mask implementation, the following ratios are introduced:

$$\begin{aligned} SIR_S &= 10\log_{10}\frac{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|STFT_x\left(n,k\right)B_S\left(n,k\right)\right|^2}{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|STFT_I\left(n,k\right)B_S\left(n,k\right)\right|^2} \\ SIR_{L1} &= 10\log_{10}\frac{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|LPFT_x^1\left(n,k\right)B_{L1}\left(n,k\right)\right|^2}{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|LPFT_I^1\left(n,k\right)B_{L1}\left(n,k\right)\right|^2} \\ SIR_{L2} &= 10\log_{10}\frac{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|LPFT_x^2\left(n,k\right)B_{L2}\left(n,k\right)\right|^2}{\sum\limits_{n=1}^{L}\sum\limits_{k=1}^{N}\left|LPFT_I^2\left(n,k\right)B_{L2}\left(n,k\right)\right|^2} \end{aligned} \tag{16}$$

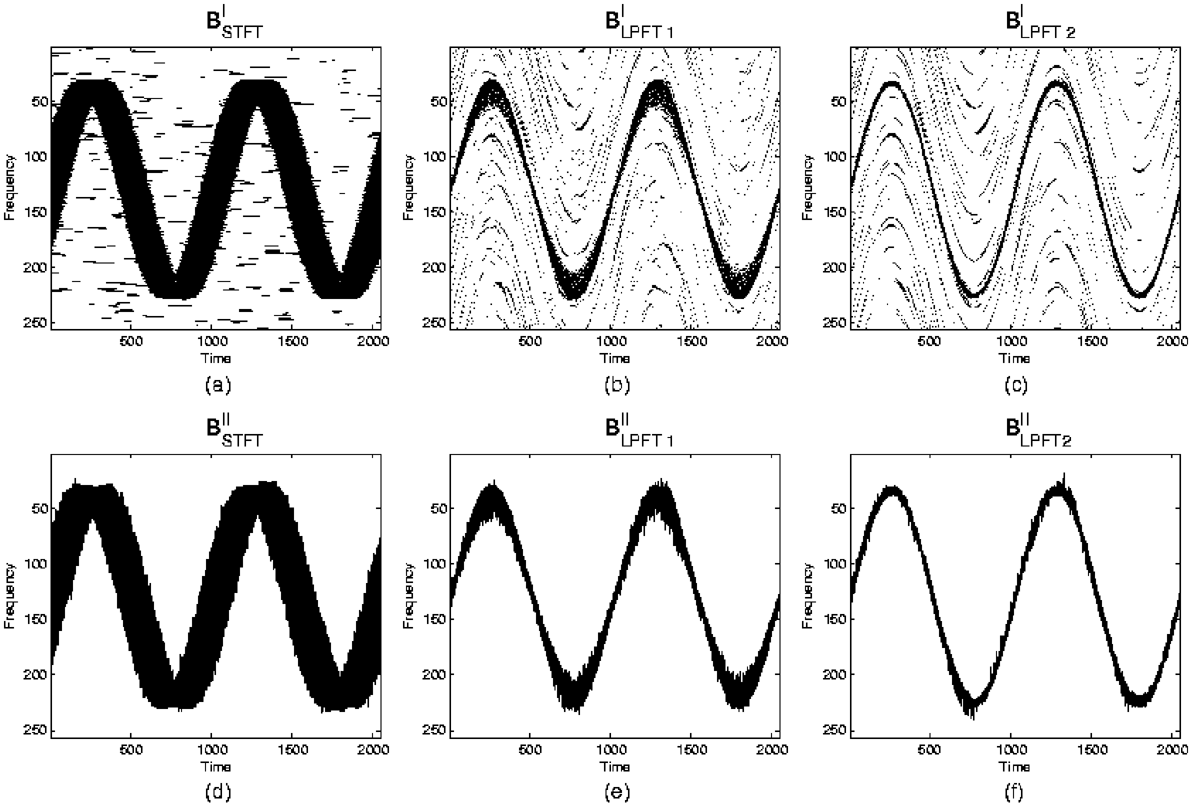
where $B_S\left(n,k\right)$, $B_{L1}\left(n,k\right)$ and $B_{L2}\left(n,k\right)$ respectively represent binary masks obtained in the STFT, the first and second order LPFT based filtering procedures.

3.1 Type I binary mask

The first adopted binary mask is trivial, i.e., it is assumed to excise all frequency bins of the transform, whether corrupted by interference or not, that exceed some threshold value. The following threshold value will be assumed [19]:

$$T_1 = E\left[\left|STFT_{x+\xi}\left(n,k\right)\right|^2\right] + 2\sqrt{Var\left[\left|STFT_{x+\xi}\left(n,k\right)\right|^2\right]} \tag{17}$$

where $E\left[\cdot\right]$ and $Var\left[\cdot\right]$ respectively represent the expectation and variance operator. Clearly, $STFT_{x+\xi}\left(n,k\right)$ represents the STFT of the sum $x\left(n\right) + \xi\left(n\right)$.



(a) (b) (c)

(d) (e) (f)

Figure 1: *Sinusoidal FM interference case. First row: Type I binary masks for (a) STFT, (b) LPFT*^{1} *and (c) LPFT*^{2} *based interference excision. Second row: Type II binary masks for (d) STFT, (e) LPFT*^{1} *and (f) LPFT*^{2} *based interference excision. Zero values are shown in black.*

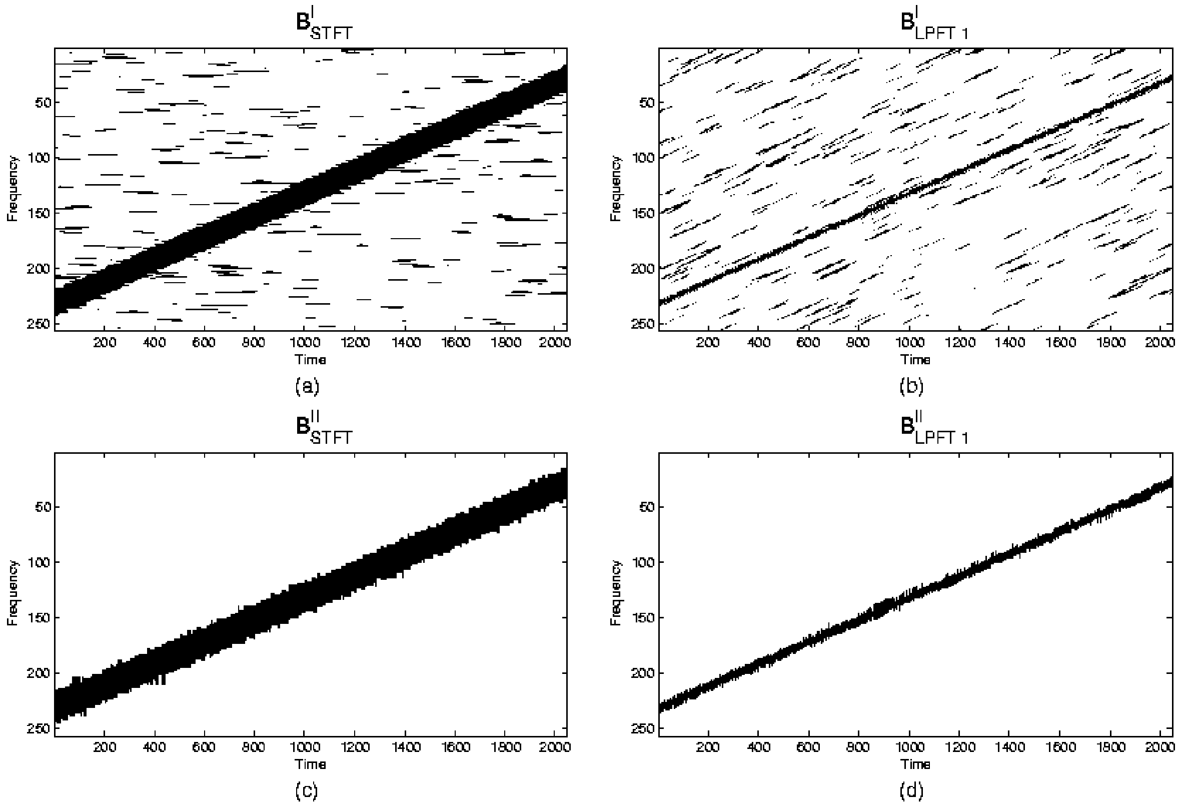


Figure 2: *LFM interference case. First row: Type I binary masks for (a) STFT and (b) LPFT*^{1} *based interference excision. Second row: Type II binary masks for (c) STFT and (d) LPFT*^{1} *based interference excision. Zero values are shown in black.*

The advantage of this type of binary mask is a simple hardware realization. However, its drawback is the removal of a certain number of frequency bins that are not corrupted by interference. Moreover, the strongest frequency components of the radar signal are eliminated in this manner.

The first and third rows of Table 1 give values of SIR ratios (Equation 16), averaged over 100 realizations. Binary masks for one realization of the STFT, the first and second order LPFT based filtering in the sinusoidal FM interference case, denoted as $\mathbf{B}_S^I$, $\mathbf{B}_{L1}^I$ and $\mathbf{B}_{L2}^I$, are depicted in Figures 1(a), (b) and (c), respectively. Corresponding binary masks for the LFM interference case are depicted in Figures 2(a) and 2(b) with superscript I denoting the first type of binary mask. In addition, the percentage of the excised frequency bins for all implemented transforms, averaged over 100 runs, is shown in the first and third rows of Table 2. Needless to say, the second order LPFT has not been calculated into the LFM case since the first order LPFT completely focuses LFM interference in a narrow band.

3.2 Type II binary mask

The second adopted binary is more sophisticated than the first one as it removes only corrupted frequency bins around the spectral peak at the current time instant. It is obtained by means of the following steps.

Step 1. Set the binary mask $B\left(n,k\right)$ to all ones and set $n=1$.

Step 2. If $n>L$ exit; otherwise detect the maximum of $\left|STFT_r\left(n,k\right)\right|$ (or $\left|LPFT_r^M\left(n,k\right)\right|$) at the current time instant n. Let the frequency index of the maximum be k_1 and set $k_2=k_1$.

Step 3. As long as $\left|STFT_r\left(n,k_2\right)\right|>\left|STFT_r\left(n,k_2-1\right)\right|$ or $\left|STFT_r\left(n,k_2\right)\right|^2>T_2$, set $B\left(n,k_2\right)=0$ and $k_2=k_2-1$.

Step 4. Set $k_2=k_1+1$. As long as $\left|STFT_r\left(n,k_2\right)\right|>\left|STFT_r\left(n,k_2+1\right)\right|$ or $\left|STFT_r\left(n,k_2\right)\right|^2>T_2$, set $B\left(n,k_2\right)=0$ and $k_2=k_2+1$.

Step 5. Set $n=n+1$ and go to step 2.

Here, T_2 represents the threshold value defined as

$$T_2=E\left[\left|STFT_{x+\xi}\left(n,k\right)\right|^2\right]+\sqrt{Var\left[\left|STFT_{x+\xi}\left(n,k\right)\right|^2\right]}. \qquad (18)$$

The advantage of the binary mask defined in this way is the sophisticated interference removal. We begin with a position of an interference spectral peak, at the needed

Table 1: *SIR for Type I and Type II Binary Masks*

Interference	Binary mask	STFT	LPFT^1	LPFT^2
Sin FM	Type I	7.49 dB	11.66 dB	13.76 dB
Sin FM	Type II	16.08 dB	20.41 dB	25.3 dB
Lin FM	Type I	12.62 dB	16.58 dB	–
Lin FM	Type II	24.1 dB	30.88 dB	–

Table 2: *Excised Bins Percentage for Type I and Type II Binary Masks*

Interference	Binary mask	STFT	LPFT^1	LPFT^2
Sin FM	Type I	33.49%	12.03%	8.4%
Sin FM	Type II	33.32%	10.18%	6.03%
Lin FM	Type I	14.1%	6.81%	–
Lin FM	Type II	12.12%	4.11%	–

time instant n, and set $B(n,k) = 0$ for all frequency bins k of the transform that are corrupted by the interference. This procedure is performed as long as the absolute value of the current frequency bin is greater than the adjacent one or its squared absolute value is greater than the adopted threshold value defined by (18). Furthermore, frequency bins of the transform that are not corrupted by an interference remain intact. The drawback of this binary mask is a rather complicated hardware realization.

The second and fourth rows of Table 1 present obtained values of ratios (16), averaged over 100 realizations. Binary masks for one realization of the STFT, the first and second order LPFT based filtering in the sinusoidal FM interference case, denoted as $\mathbf{B}_S^{II}$, $\mathbf{B}_{L1}^{II}$ and $\mathbf{B}_{L2}^{II}$, are depicted in Figures 1(d), 1(e) and 1(f), respectively. Corresponding binary masks for the LFM interference case are depicted in Figures 2(c) and 2(d). Superscript II denotes the second type of binary mask. Again, the percentage of the excised frequency bins for all the three implemented transforms, averaged over 100 runs, is presented in the second and fourth row of Table 2.

3.3 Discussion

Despite the fact that the removed area is approximately the same (see Table 2), the second type of binary mask is characterized by a significant improvement in SIR performance compared to the first type, as shown by results given in Table 1. The reason for such behavior is the fact that the first type of binary mask eliminates the strongest frequency components of the radar signal along with the interference components.

The STFT based filtering is outperformed by the first order LPFT based filtering, however, the second order LPFT produces the best results, since the corresponding excised area is the smallest compared to the other two. Furthermore, as can be seen from Figures 1(f) and 2(d), the number of excised frequency bins is approximately the same for each time instant, meaning that increasing the LPFT order would not provide a significant SIR improvement.

Monocomponent interference has been assumed in this analysis. If an interference is a multicomponent signal, type I binary mask and STFT can be applied without any modifications, while the procedure for the type II binary mask implementation or LPFT needs to be modified in order to remove all interference components.

4 Simulations

Consider a noise radar operating at carrier frequency $f_0 = 10\,\mathrm{GHz}$ with bandwidth $B = 204.8\,\mathrm{MHz}$ and pulse duration of $T_r = 10\,\mu\mathrm{s}$ (or 2048 samples). The received signal is sampled at the Nyquist rate $T_s = 1/B$. The radar waveform is a complex Gaussian random signal with i.i.d (independent and identically distributed) real and imaginary parts. The transmitted signal is reflected from the single point scatterer target located at distance $r_0 = 1\,\mathrm{km}$. Let us also assume that the received signal is corrupted by a Gaussian complex noise $\xi(t)$ and interference signal $I(t)$. The received signal is of the form

$$r(t) = x(t) + I(t) + \xi(t) \tag{19}$$

where $x(t) = A_x x_t(t - t_d)$ represents a signal reflected from the target, characterized by attenuation A_x and time delay $t_d = \frac{2r_0}{c}$. Note that $r(n)$ defined by (1), represents the discrete version of (19).

The interference is assumed to be a frequency modulated signal of the form

$$I(t) = A_I e^{j\varphi_I(t)}$$

Two types of interference are analyzed:

1) Interference with sinusoidal instantaneous frequency (for example jamming signal) in the form:

$$f_I^{\sin}(t) = \frac{d\varphi_I(t)}{dt} = -\frac{3}{8} B \sin(8\pi \frac{t}{T_r}). \tag{20}$$

2) Interference with a linear instantaneous frequency, corresponding to a LFM radar operating at the same frequency band. The linear FM interference is periodic with period $\frac{T_r}{2}$ and the equation (21) is valid within the fundamental period only.

$$f_I^{lin}(t) = \frac{d\varphi_I(t)}{dt} = -2B\frac{t}{T_r} \text{ for } -\frac{T_r}{4} < t < \frac{T_r}{4} \tag{21}$$

The interference suppression is performed by using the proposed TF based filtering of the received signal.

Four cases are considered

1. No interference suppression is performed.
2. Interference suppression is performed by using STFT.
3. Interference suppression is performed by using LPFT of the first order.

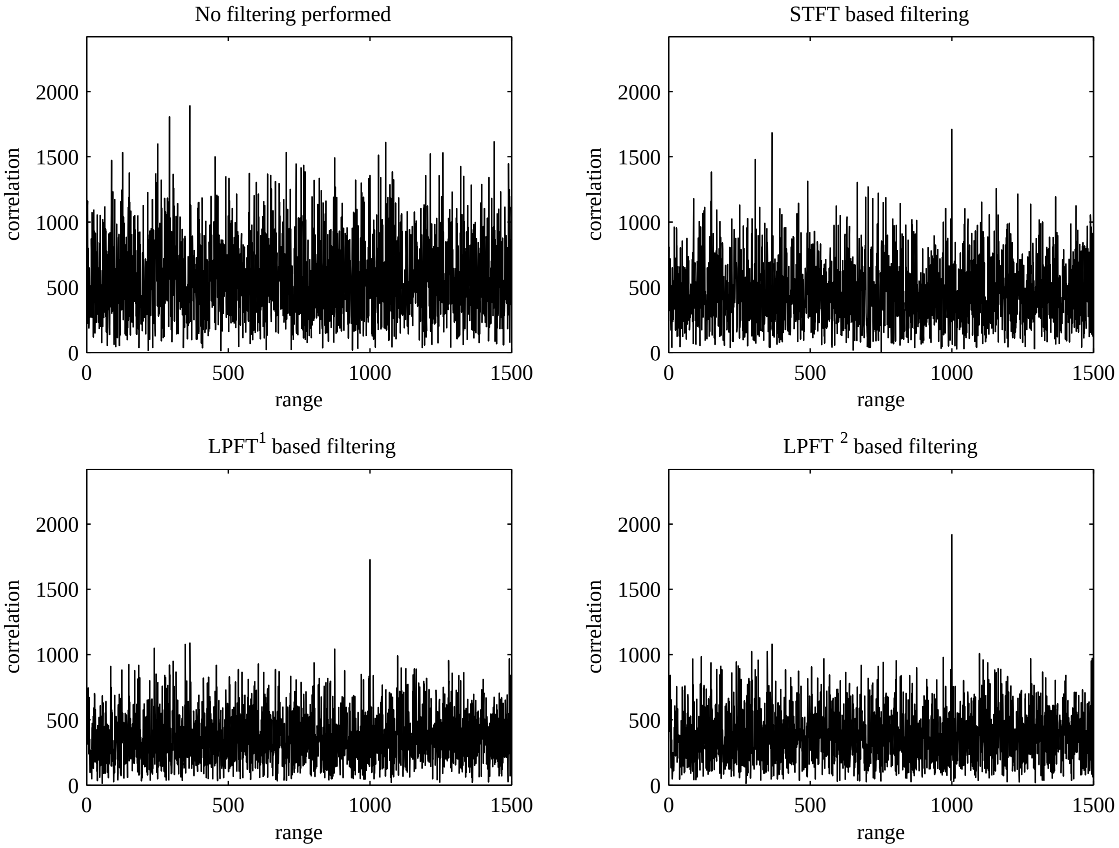


Figure 3: *Output of the correlation receiver for the single target located at* 1000 m *range with $SNR = -20$ dB and $SIR = -20$ dB when no filtering is performed (upper left), STFT based filtering is performed (upper right) first order LPFT filtering (lower left) and second order LPFT (lower right). Type II binary mask is used.*

4. Interference suppression is performed by using LPFT of the second order.

For the interference suppression, both type I and type II binary mask are used, as described in Section 3. Figure 3 presents radar outputs in all the considered cases. Note that the target is not detected when no interference suppression is performed, and the LPFT based filtering outperforms the STFT based approach.

The simulation was performed over 1000 realizations of the received signal. The probability of false target detection[1] versus SIR for $SNR = -20$dB is calculated and results are presented in Tables 3 and 5 for type I binary mask and in Tables 4 and 6 for type II binary mask.

---

[1] False target detection occures when detected maxima position of the radar output does not coincide with true target position.

SIR	No filtering	STFT	LPFT^1	LPFT^2
−20dB	27.7%	46.9%	15.3%	11.0%
−25dB	75.7%	57.1%	18.2%	11.4%
−30dB	96.7%	58.0%	20.0%	12.7%
−35dB	99.4%	63.1%	25.4%	16.0%
−40dB	99.5%	68.0%	30.6%	18.5%

Table 3: *Probability of false target detection for* $SNR = -20dB$ *and sinusoidal FM interference. Type I binary mask is used.*

SIR	No filtering	STFT	LPFT^1	LPFT^2
−20dB	28.5%	17.0%	2.1%	2.0%
−25dB	75.4%	18.0%	3.7%	2.7%
−30dB	96.3%	26.4%	5.2%	2.7%
−35dB	99.4%	36.6%	7.8%	2.9%
−40dB	99.4%	43.5%	10.4%	5.1%

Table 4: *Probability of false target detection for* $SNR = -20dB$ *and sinusoidal FM interference. Type II binary mask is used.*

SIR	No filtering	STFT	LPFT^1
−20dB	29.4%	17.3%	8.1%
−25dB	76.6%	17.8%	7.9%
−30dB	97.4%	16.9%	7.8%
−35dB	99.6%	19.3%	8.7%
−40dB	99.9%	21.2%	8.5%

Table 5: *Probability of false target detection for* $SNR = -20dB$ *and LFM interference. Type I binary mask is used.*

SIR	No filtering	STFT	LPFT^1
−20dB	29.5%	2.9%	1.5%
−25dB	76.2%	6.4%	1.8%
−30dB	96.4%	8.1%	1.9%
−35dB	99.3%	19.7%	1.9%
−40dB	99.7%	45.3%	2.7%

Table 6: *Probability of false target detection for* $SNR = -20dB$ *and LFM interference. Type II binary mask is used.*

As discussed in 3.3 type II binary mask outperforms type I binary mask, and the LPFT provides better results than the STFT.

5 Conclusion

The problem of nonstationary interference suppression in noise radar systems is addressed. Towards this aim, time-varying filters based on linear TF transforms, namely STFT and LPFT, are developed. The filtering is performed in the TF domain by using a binary excision mask, which removes the nonstationary interference. Two approaches to the binary mask implementation are proposed. Numerical simulations show that the TF based time-varying filtering significantly improves the probability of target detection in severe interference environments. The best results are obtained by using the second order LPFT. Results clearly demonstrate that the time-frequency based interference suppression method can significantly improve the detection performance of the noise radar systems in extremely strong nonstationary interference environments.

The proposed interference suppression method can potentially be extended to other relevant applications such as over-the-horizon radar systems (OTHR), through-wall imaging systems, phased array radar systems, global positioning satellite (GPS) receivers, global navigation satellite systems (GNSSs), etc. Another important application of this method is jammer rejection in the spread spectrum (SS) communication systems. Different methods have been proposed for rejection or mitigation of interferences of this kind, in order to improve interference immunity of SS systems and provide more reliable receiving and decoding of the useful signal. The proposed method presents another viable approach to jammer mitigation and enhances the performance of the SS receiver in such severe interfering environment. The proposed method may also be extended to the case of multiple jammers. This method can generally be applied whenever the desired signal is corrupted by broadband interferences characterized by narrowband instantaneous bandwidths.

References

[1] X. Xu, “Impact of Different Correlation Receiving Techniques on the Imaging Performance of UWB Random Noise,” *Geoscience & Remote Sensing Symposium,* IGARSS’03, Vol. 7, pp. 4,525-4,527, 2003.

[2] K.A. Lukin, “Developments of Noise Radar Technology in LNDES IRE NASU,” First International Workshop on the Noise Radar Technology, *NTRW 2002 Proceedings,* pp. 90-96, Yalta, Ukraine, 2002.

[3] S.R.J. Axelsson, “On the Theory of Noise Doppler Radar,” Geoscience and Remote Sensing *Symposium Proceedings 2000,* pp. 856-860, Honolulu, USA, 2000.

[4] S.R.J. Axelsson, “Noise Radar For Range/Doppler Processing and Digital Beamforming Using Low-Bit ADC,” *IEEE Trans. on Geoscience and Remote Sensing,* Vol. 41, No. 12, pp. 2,703-2,720, 2003.

[5] K.A. Lukin, “The Principles of Noise Radar Technology,” First International Workshop on the Noise Radar Technology, *NTRW’2002 Proceedings,* pp. 13-22, Yalta, Ukraine, 2002.

[6] D.C. Bell and R.M. Naryanan, “Theoretical Aspects of Radar Imaging Using Stohastic Waveforms,” *IEEE Trans. on Signal Processing,* Vol. 49, No. 2, pp. 394-400, 2001.

[7] R. Stephan and H. Loele, “Theoretical and Practical Characterization of a Broadband Random Noise Radar,” *Dig. 2000 IEEE MTT-S International Microwave Symp.,* pp. 1,555-1,558, Boston, MA, 2000.

[8] R.M. Narayanan, Y. Xu, P.D. Hoffmeyer and J.O. Curtis, “Design, performance, and implementation of a coherent ultrawideband random noise radar,” *Opt. Eng.,* Vol. 37, No. 6, pp. 1,855-1,869, 1998.

[9] K.A. Lukin, “Millimeter wave noise radar technology,” *Proc. 3rd Int. Kharkov Symp.,* Physics Engineering illimeter and SubmillimeterWaves, Kharkov, Ukraine, pp. 94-97, 1998.

[10] D.S. Garmatyuk and R.M. Narayanan, “Ultra-wideband continuouswave random noise arc-SAR,” *IEEE Trans. Geosci. Remote Sensing,* Vol. 40, pp. 2,543-2,552, 2002.

[11] Y. Xu, R.M. Narayanan, X. Xu and J.O. Curtis, “Polarimetric processing of coherent random noise radar data for buried object detection,” *IEEE Trans. Geosci. Remote Sensing,* Vol. 39, pp. 467-478, 2001.

[12] C.P. Lai, R.M. Narayanan and G. Colkowski, "Through wall surveillance usig ultrawideband random noise radar," *25 th Army Science Conference,* Florida, November 27-30, Orlando, Florida, pp. 1-4, 2006.

[13] T. Thayaparan, L. Stankovic, and M. Dakovic, M, "Mutual Interference and Low Probability of Interception, " Colonge, Germany, pp. 576-579, 2007.

[14] T. Thayaparan and C. Wernik, "Noise Radar Technology Basics, " DRDC Ottawa TM 2006-266, Defence R&D Canada - Ottawa, 2006.

[15] Lj. Stanković, "On the time-frequency analysis based filtering", *Annales des Telecommunications*, Vol.55, No.5-6, May 2000, pp.216-225.

[16] F. Hlawatsch and F. Boudreaux-Bartels, "Linear and quadratic time-frequency signal representations," *IEEE Signal Processing Magazine*, vol.9, pp. 21–67, Apr. 1992.

[17] Lj. Stanković and S. Djukanović, "Order adaptive local polynomial FT based interference rejection in spread spectrum communication systems," *IEEE Transactions on Instrumentation and Measurement*, vol.54, pp. 2156-2162, Dec. 2005.

[18] V. Katkovnik, "A new form of the Fourier transform for time-varying frequency estimation," *Signal Processing*, vol.47, no.2, pp. 187-200, 1995.

[19] Kay, S. M. (1993). Fundamental of statistical signal processing: estimation theory, *Prentice Hall Signal Processing Series,* New Jersey, USA.

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The problem addressed in this memorandum is nonstationary interference suppression in noise radar systems. Towards this aim, linear time-frequency (TF) transforms, short time Fourier transform (STFT) and local polynomial Fourier transform (LPFT) are used as a means of signal representation. The noise radar return signal is a wideband random signal occupying the whole TF plane, while the interference signal is well concentrated in the TF plane. This implies that the filtering of the received signal can be performed by using a binary mask to excise only a portion of the TF plane corrupted by the interference. Simulations carried out on the radar return signal corrupted by an extremely strong nonstationary interferences, covering the same time and frequency ranges. Results confirm the effectiveness of the proposed method.

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