Beamspace post-Doppler STAP in ground-based rotating radar systems

Marc Oudin, Jean-Pierre Delmas, Claude Adnet, Frédéric Barbaresco

BEAMSPACE POST-DOPPLER STAP IN GROUND-BASED ROTATING RADAR SYSTEMS

*Marc Oudin, Jean-Pierre Delmas**

GET/INT
9 rue Charles Fourier, 91011 Evry Cedex, France
phone:(33)1 60 76 45 44, fax:(33)1 60 76 44 33
marc.oudin@int-edu.eu

Claude Adnet, Frédéric Barbaresco

Thales/TR6/SR/PST
Hameau de Roussigny
91470 Limours, France

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ABSTRACT

In this paper, we consider the problem of using Space-Time Adaptive Processing (STAP) in ground-based rotating radars, in the case where no jamming alone reference is available. Thus, we propose the use of a STAP algorithm, in which adaptive processing is applied in Beam post-Doppler space. First, we give design rules for the implementation of this processing, after considering two cases depending on the knowledge of the jammers' DOAs and investigating the influence of the number of Doppler filters on performance. Then, we show by simulations that the proposed processing is robust to antenna rotation and has the advantage of having both an high convergence speed with the number of training samples and a low implementation complexity.

1. INTRODUCTION

In radar systems, the detection of moving targets is enabled by clutter and jamming mitigation using temporal and spatial processings. Those ones exploit the characteristics of speed for clutter and of Direction Of Arrival (DOA) for jammers. In ground-based staring antenna radar systems, Doppler processing and beamforming are common building blocks which are efficient to filter motionless clutter and jammers. Indeed, they can respectively mitigate low Doppler frequency clutter (corresponding to low speed clutter) and constant DOA jammers. However, when the antenna radar is rotating, those standard processings degrade because clutter is seen with a certain speed and the jammers' positions vary with time. The rotation makes indeed position dependent on time. In airborne radar systems, there also exists a relation between these two parameters. Indeed, the Doppler frequency of clutter depends on its DOA. STAP (Space-Time Adaptive Processing) which was introduced to the airborne radar community in 1973 in [1] and further extensively researched (e.g., see [2, 3]), is an effective way of taking into account this relation for space-time processing. In practical cases, fully adaptive STAP use is limited by minimal samples-support training [4]. Two main categories of alternate STAP algorithms are then used (e.g., see [5]). The first one is Reduced Dimension (RD) STAP and consists in applying data independent transformations on data before adaptive filtering. The second one is Reduced Rank (RR) STAP and consists in applying data dependent transformations on the data [6, 7]. Both categories allow to increase the convergence speed of STAP algorithms (e.g., see [8]).

In this paper, we consider the problem of using STAP with ground-based rotating radars. This question has already been investigated in [9] where the use of a separable spatial then temporal STAP processing has been proposed. However, this processing requires that jamming alone reference data are available to compute adaptive spatial filters, or that a preprocessing of training data is used. Since those reference data may not be available and the effectiveness of preprocessing degrades with clutter decorrelation and antenna rotation [10], this processing cannot be used in every scenarios. Here, we propose a space-time processing which does not require the availability of jamming alone reference. In particular, we propose a space-time processing algorithm, in which adaptive filtering is applied in Beam post-Doppler space. We consider two cases depending on the knowledge of the jammers' DOAs and investigate the influence of the number of Doppler filters on performance. Then, we show by simulations that a small number of beams and Doppler filters is sufficient to reach good performance. Therefore, the proposed processing has the advantage of having both an high convergence speed and a low implementation complexity.

2. DATA MODEL

Let suppose that the environment be composed of jammers, clutter, thermal noise and a moving target. The ground-based radar emits an M- pulse waveform (CPI - Coherent Processing Interval) at pulse repetition T. In each PRI (Pulse Repetition Interval), the data is divided into two sets called primary and secondary data. The primary data consists of the samples to be filtered and is composed by interference (jammers and clutter), thermal noise and possibly signal. The secondary data is the training data, and is supposed to be only made of

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jamming, clutter and thermal noise components. Let denote K, the number of secondary samples in each PRI. We suppose that the J jammer signals $\{\mathbf{j}_k^{(m,j)}\}_{k=1..K,m=1..M,j=1..J}$ are zero-mean, with power σ_j^2. They are spatially correlated, but temporally white and independant from each other. The clutter is modelled by elementary reflectors. Those ones are supposed to be motionless, spatially and from PRI to PRI correlated but white from sample to sample. Like the jammers, they are zero-mean, with power $\sigma_c^2(\theta)$ depending on their DOA and mutually independent. We suppose that thermal noise $\{\mathbf{n}_k^{(m)}\}_{k=1..K,m=1..M}$ is modelled by a white complex process, with power σ_n^2 (that will be unitary in the following). Finally, the signal is considered as deterministic, with unknown power σ_s^2, but known direction and speed. We note $\{\mathbf{x}_k^{(m)}\}_{k=1..K,m=1..M}$ the N-dimensional secondary data (N being the number of sensors) and have:

$$\mathbf{x}_k^{(m)} = \sum_{j=1}^{J} \mathbf{j}_k^{(m,j)} + \int_0^{2\pi} \mathbf{c}_k^{(m)}(\theta) d\theta + \mathbf{n}_k^{(m)}$$

where $\mathbf{j}_k^{(m,j)} = j_k^{(m,j)} \boldsymbol{\phi}_k^{(m,j)}$, $\mathbf{c}_k^{(m)}(\theta) = c_k(\theta)\boldsymbol{\phi}_k^{(m)}(\theta)$ and $\boldsymbol{\phi}_k^{(m)}(\theta)$ is the steering vector for the k^{th} sample of the m^{th} PRI at DOA θ. Let now note $\mathbf{X}_{k=1..K}$ the NM-dimensional secondary space-time data samples. The space-time arrangement order is the following:

$$\mathbf{X}_k \overset{\text{def}}{=} \begin{pmatrix} \mathbf{x}_k^{(1)} \\ \vdots \\ \mathbf{x}_k^{(M)} \end{pmatrix} = \sum_{j=1}^{J} \mathbf{J}_k^{(j)} + \int_0^{2\pi} \mathbf{C}_k(\theta) d\theta + \mathbf{N}_k$$

where $\mathbf{J}_k^{(j)} = \begin{pmatrix} \mathbf{j}_k^{(1,j)} \\ \vdots \\ \mathbf{j}_k^{(M,j)} \end{pmatrix}$, $\mathbf{C}_k(\theta) = c_k(\theta)\boldsymbol{\Phi}_k(\theta,0)$ with $\boldsymbol{\Phi}_k(\theta,f) = \begin{pmatrix} \phi_T^{(1)}(f)\boldsymbol{\phi}_k^{(1)}(\theta) \\ \vdots \\ \phi_T^{(M)}(f)\boldsymbol{\phi}_k^{(M)}(\theta) \end{pmatrix}$ ($\phi_T^{(m)}(f)$ being dephasing due to a normalized Doppler frequency f) and $\mathbf{N}_k = \begin{pmatrix} \mathbf{n}_k^{(1)} \\ \vdots \\ \mathbf{n}_k^{(M)} \end{pmatrix}$.

Then, the space-time secondary data covariance matrix of the k^{th} sample is given by:

$$\mathbf{R}_k = \mathbf{R}_{J,k} + \int_0^{2\pi} \sigma_c^2(\theta)\boldsymbol{\Phi}_k(\theta,0)\boldsymbol{\Phi}_k^H(\theta,0)d\theta + \sigma_n^2\mathbf{I}_{MN}$$

with:

$$\mathbf{R}_{J,k} = \sigma_J^2 \sum_{j=1}^{J} \begin{pmatrix} \boldsymbol{\phi}_k^{(1,j)}\boldsymbol{\phi}_k^{(1,j)H} & & \mathbf{O} \\ & \ddots & \\ \mathbf{O} & & \boldsymbol{\phi}_k^{(M,j)}\boldsymbol{\phi}_k^{(M,j)H} \end{pmatrix}$$

Finally, in primary data, the signal contribution of a target at DOA θ_s and Doppler frequency f_s, is noted $\mathbf{S}_k = s_k\boldsymbol{\Phi}_k(\theta_s, f_s)$.

We consider a uniform linear antenna and a situation where it is rapidly rotating to the CPI scale, but slowly compared to a PRI. Therefore, we will make the following approximation: $\boldsymbol{\phi}_k^{(m)}(\theta) \approx \boldsymbol{\phi}^{(m)}(\theta)$ which implies $\boldsymbol{\Phi}_k(\theta,f) \approx \boldsymbol{\Phi}(\theta,f)$ and $\mathbf{R}_k \approx \mathbf{R}$. Then, we suppose that the antenna is rotating at speed ω rad/s. Therefore, a target seen at DOA θ at initial time will be seen at DOA $\theta + \omega t$ at time t.

In order to evaluate the performance of the proposed processing, we will introduce the space-time filter $\mathbf{W}$. Then, our performance criterium will be the space-time SINR defined as: $\text{SINR} = \frac{P_{res}(signal)}{P_{res}(noise)}$ with $P_{res}(signal) = \sigma_s^2 \left|\mathbf{W}^H\boldsymbol{\Phi}\right|^2$ and $P_{res}(noise) = \mathbf{W}^H\mathbf{R}\mathbf{W}$, where $\boldsymbol{\Phi} \overset{\text{def}}{=} \boldsymbol{\Phi}(\theta_s, f_s)$ is the steering vector of the target.

3. PRESENTATION OF THE PROPOSED PROCESSING

3.1. Principle of the processing

The space-time processing is made of three steps. The first one consists in forming beams from primary and secondary data. Then, Doppler filtering is applied to each beam. Finally, an adaptive space-time algorithm is implemented. Secondary data are used to estimate the filters that are then applied to primary data. Figure 1 summarizes the processing:

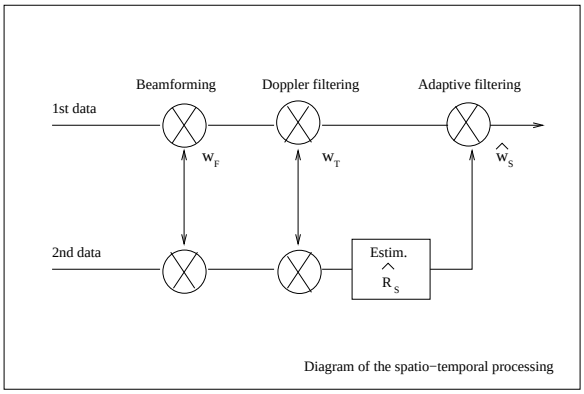

Figure 1 - Diagram of the space-time processing

At first step, beamforming consists in forming a beam in target direction and other beams at different directions. To make effective jamming mitigation, the number of beams must be at least equal to $J+1$. The first beam (or main beam) is formed in the target direction. Then, as for the choice of other beams (or auxiliary beams) DOAs, if a priori knowledge is available about jammers DOAs, beams can be formed in those directions. Otherwise, a beam fan of orthogonal beams may be formed in order to cover a certain angular extension (e.g., see [11, Section 6.9]). Then, to avoid that beams' directions change from PRI to PRI, beamforming's direction w.r.t. antenna is updated at each PRI. Finally, for the algorithm implementation, three main questions must be answered:

- How to form auxiliary beams ?

- How many Doppler filters must be used ?
- How to choose the Doppler filters normalized frequencies ?

Those questions will be considered in Section 4, where the influence of each of the above parameters is investigated analytically or by simulations. Now, we detail the expression of the filter and the choice of the adaptive space-time algorithm.

3.2. Expression of the STAP filter

In this subsection, we derive the expression of the space-time filter $\mathbf{W}$ to be applied to primary data. The succession of the steps presented in the previous subsection is equivalent to the use of the following filter:

$$\mathbf{W} = \mathbf{A}^H \mathbf{B}^H \mathbf{w}_S \tag{1}$$

where $\mathbf{A}$ is of size $(PM \times NM)$ and corresponds to the first step and where P is the number of beams and the beamformers are $(\mathbf{w}_{F_p,m})_{p=1..P,m=1..M} = \boldsymbol{\phi}^{(m)}(\theta_p)$, where the choice of DOAs $(\theta_p)_{p=2...P}$ will be considered in the following. Then, $\mathbf{B}$ is of size $(PQ \times PM)$ and corresponds to the second step, where $\mathbf{w}_{T,1} = \boldsymbol{\phi}_T(f_s)$ is the first Doppler filter. Then, the other Doppler filters will be chosen such that $(\mathbf{w}_{T,q})_{q=2...Q} = \boldsymbol{\phi}_T(f_q)$ where the choice and the number of the normalized frequencies $(f_q)_{q=2...Q}$ will be considered in the following. Finally, $\mathbf{w}_S$ is the adaptive space-time filter applied on Beamspace post-Doppler data during the third step. This one is formed by computing the MVDR (Minimum Variance Distortionless) filter (e.g., see [11]):

$$\mathbf{w}_S = \frac{\mathbf{R}_S^{-1}\mathbf{v}}{\mathbf{v}^H \mathbf{R}_S^{-1}\mathbf{v}} \tag{2}$$

where

$$\mathbf{R}_S = \mathbf{BARA}^H \mathbf{B}^H \tag{3}$$

represents the noise covariance matrix from secondary data after that the two first steps are implemented. Then $\mathbf{v} = \mathbf{BA\Phi}$ is of dimension PQ. According to the taxonomy proposed in [2] for STAP processings, the proposed algorithm will be called Beam post-Doppler Space Time Adaptive Processing (BDSTAP) in the following.

4. CHOICE OF THE PROCESSING PARAMETERS

Now, we analyze the choice of the beams DOAs $(\theta_p)_{p=2...P}$ and of the normalized frequencies $(f_q)_{q=2...Q}$. First, let note that after beamforming with rotation compensation, Doppler spread of clutter echoes is limited, as analyzed in [9]. Therefore, apart from powerful echoes seen in the antenna sidelobes, clutter can be efficently mitigated by standard non adaptive Doppler filtering, corresponding to the case $Q = 1$. Consequently, the main difficulty of the proposed processing will be jamming mitigation that we now analyze.

To simplify the analysis, we assume that only one jammer is present and that we form two beams, one in the target DOA and the other one in another DOA. First, we consider the case $Q = 1$, which corresponds to space only adaptive processing, after beamforming and Doppler filtering and compute the steady-state SINR as a function of the second beam DOA θ_2 and the scenario parameters. When a priori knowledge about the jammer DOA is available, an intuitive choice of the second beam DOA is the jammer direction ($\theta_2 = \theta_j$). However, if this choice leads to optimal performance in terms of SINR in a staring antenna context, we show that antenna rotation leads to performance losses which increase with the jammer DOA. Then, based on the expression of the steady-state SINR, we deduce a rule of thumb for the choice of a second DOA, for which the losses due to antenna rotation are limited. Then, we consider the case $Q = 2$. Thus, we show that a proper choice of the second Doppler frequency filter, can allow one to compensate for SINR losses due to antenna rotation, in the case where the second beam is formed in the jammer direction.

4.1. Jamming mitigation with $Q = 1$

Here, we analyze the influence of antenna rotation on the steady-state SINR, as a function of the jammer and second beam DOAs. Since the MVDR algorithm is implemented (2), the signal power is kept constant and equal to $P_{res}(signal) = \sigma_s^2$ after BDSTAP. Therefore, the losses in SINR will correspond to the increase of the noise resulting power. By definition, $P_{res}(noise) = \mathbf{W}^H \mathbf{R} \mathbf{W}$. Then, after using (1), (2) and (3), we have:

$$P_{res}(noise) = \frac{1}{\mathbf{v}^H \mathbf{R}_S^{-1} \mathbf{v}} \tag{4}$$

where $\mathbf{v} \approx NM(1 \quad 0)^T$. Then, after straightforward algebra manipulations, we show that the noise resulting power can be approximated by

$$\begin{aligned} P_{res}(noise) \quad &\approx \quad \frac{1}{(NM)^2} \left(\sum_{m=1}^{M} (\sigma_J^2 \left|\beta_m\right|^2 + \sigma_n^2 N) \right. \\ &- \quad \left. \frac{\left| \sum_{m=1}^{M} \sigma_J^2 \gamma_m^* \beta_m + \sigma_n^2 \delta_m \right|^2}{\sum_{m=1}^{M} (\sigma_J^2 \left|\gamma_m\right|^2 + \sigma_n^2 N)} \right) \end{aligned} \tag{5}$$

with for $1 \leq m \leq M$, $\beta_m = \boldsymbol{\phi}^{(m)}(\theta_s)^H \boldsymbol{\phi}^{(m)}(\theta_j)$, $\gamma_m = \boldsymbol{\phi}^{(m)}(\theta_2)^H \boldsymbol{\phi}^{(m)}(\theta_j)$ and $\delta_m = \boldsymbol{\phi}^{(m)}(\theta_s)^H \boldsymbol{\phi}^{(m)}(\theta_2)$. Based on (5), we first give an approximate expression of the normalized SINR when $\theta_2 = \theta_j$, to make the influence of antenna rotation on performance explicit. Then, we give a rule of thumb for chosing the second beam DOA θ_2.

4.1.1. With a second beam formed in the jammer DOA

When the second beam is formed in the jammer direction, we have $\gamma_m = N$ and $\beta_m = \delta_m$ for $1 \leq m \leq M$. Using

approximation $N\sigma_J^2 \gg \sigma_n^2$, (5) may be approximated by

$$P_{res}(noise) \approx \frac{\sigma_n^2}{NM} + \frac{\sigma_J^2}{(NM)^2}\left(\sum_{m=1}^{M}|\beta_m|^2 - \frac{\left|\sum_{m=1}^{M}\beta_m\right|^2}{M}\right) \quad (6)$$

Then, in order to make expression (6) explicit, we assume $\omega T \ll 1$ and $M \gg 1$. After a second order Taylor expansion and straightforward algebra manipulations, we obtain:

$$P_{res}(noise) \approx \frac{\sigma_n^2}{NM} + \sigma_J^2 \frac{M}{12N^2}|\alpha|^2 \omega^2 T^2$$

with $\alpha = j\pi(\cos(\theta_s) - \cos(\theta_j)) \sum_{n=1}^{N-1} n e^{jn\pi(\sin(\theta_s)-\sin(\theta_j))}$, from which we obtain the expression of the normalized SINR

$$\text{SINR}_{norm} \approx \frac{1}{1 + \frac{\sigma_J^2}{\sigma_n^2}\frac{M^2}{12N}|\alpha|^2 \omega^2 T^2} \quad (7)$$

where $\text{SINR}_{norm} = \frac{\sigma_n^2 \text{SINR}}{\sigma_s^2 NM}$. To illustrate this result, we plot in Figure 2 the approximate value of SINR_{norm} given by (7) and compare it to its actual value obtained from (4). The parameters are $M = 10$, $N = 60$, $T = 0.002$ sec., $\theta_s = 0$ deg., $f_s = 0.1$ and $\sigma_J^2 = 30$ dB.

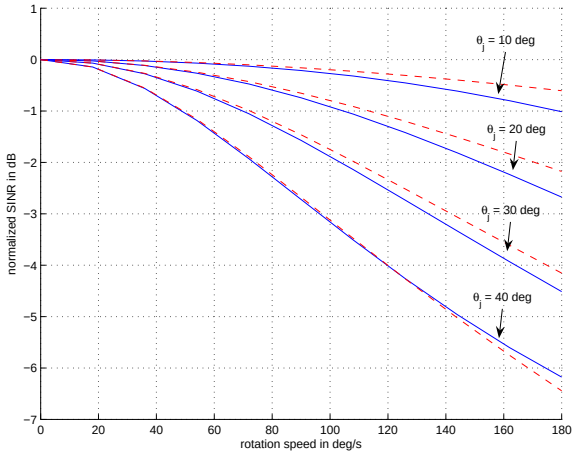

Figure 2 - Comparison between (–) actual and (- -) approximate (7) expressions of SINR_{norm} for different values of θ_j

First, we observe that actual and approximate curves correspond for low values of rotation speed. Then, we note that the steady state performance degradation increases with the DOA. For values of jammers' DOA close to that of the signal, the degradation is limited. For instance, it will be less than 1 dB degradation for jammers that are less than 10 deg. distant from the signal, with the chosen parameters. However, for a jammer at DOA $\theta_j = 40$ deg., there are about 6 dB SINR losses at a rotation speed of 180 deg/s. Physically, those performance losses are due to the fluctuations of sidelobes after rotation compensation which increase at DOAs distant from the focalisation direction. Consequently, the jammer signal becomes nonstationary from PRI to PRI which makes its mitigation difficult after Doppler filtering. To take this effect into account, a second Doppler filter can be used, allowing one to introduce time adaptivity in the processing. This point is analyzed in the next Section where we present simulations with $Q = 2$ to show the resulting improvement of performance in terms of jamming mitigation. Before that, we consider an alternative choice for θ_2.

4.1.2. On the choice of the second beam

Though optimal in a staring antenna context, we have seen previously that the choice of a second beam in the jammer direction leads to SINR losses when the antenna rotates. Here, we propose another choice of the second beam DOA based on the analysis of noise resulting power (5). Assuming that the thermal noise contribution in (5) can be neglected w.r.t. the jamming contribution, the noise resulting power is minimized when $\frac{\left|\sum_{m=1}^{M}\gamma_m^*\beta_m\right|^2}{\sum_{m=1}^{M}|\gamma_m|^2}$ is maximized. Using the Cauchy-Schwarz inequality, this ratio is maximized for $\gamma_m \propto \beta_m$, which is obtained by chosing $\theta_2 = \theta_s$. However, this choice leads to a singular reduced-dimension matrix $\mathbf{R}_S$ and is therefore impossible. Consequently, we propose chosing a second beam equal to the first orthogonal beam to the first beam (i.e. by chosing $\sin(\theta_2) = \sin(\theta_s) \pm \frac{2}{N}$). To illustrate the influence of the second beam DOA on the steady-state SINR, we plot in Figure 3 the normalized SINR as a function of antenna rotation, with $\theta_j = 40$ deg., for three values of θ_2. The first one is $\theta_2 = 1.9$ deg. and corresponds to the formation of the first orthogonal beam to the first beam (with $\theta_2 > 0$). Then, two other beams on both sides of the latter beam are formed, respectively with $\theta_2 = 1.5$ deg. or $\theta_2 = 2.5$ deg.

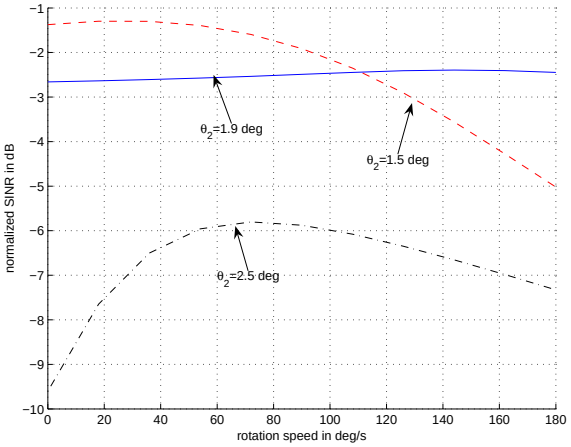

Figure 3 - Normalized SINR for different values of θ_2

We observe that the choice of an orthogonal beam is not optimal in terms of SINR but leads to robust performance w.r.t. antenna rotation. On the contrary, the performance with the other choices of second beam DOA are very dependent on antenna rotation speed.

4.2. Jamming mitigation with $Q = 2$

Now, we perform Monte Carlo simulations to plot the normalized SINR after BDSTAP processing, as a function of the normalized Doppler frequency of the second filter f_2. The jammer DOA is equal to $\theta_j = 40$ deg. (thus corresponding to a steady state performance loss in SINR of about 6 dB (see Figure 2). Then, the number of samples used for the estimation of the BDSTAP covariance matrix $\mathbf{R}_S$ is equal to $K = 120$. In Figure 4, we plot the normalized SINR in the case where the second beam is formed in the jammer direction (dashed plot with $\theta_2 = 40$ deg.) and in the case where the second beam is orthogonal to the first beam (with $\theta_2 = \arcsin(\frac{2}{N}) = 1.9$ deg.).

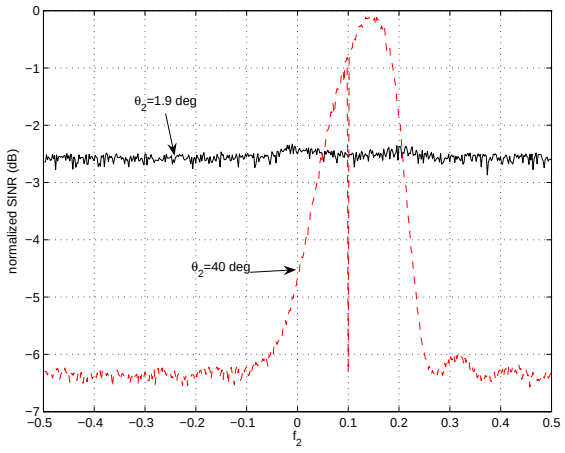

Figure 4 - Influence of the choice of f_2 on the normalized SINR

When $\theta_2 = 40$ deg., we observe that there is no SINR improvement when $f_2 \leq -0.15$ and $f_2 \geq 0.2$, but when $f_2 \approx 0.15$, the jammer is nearly cancelled. Consequently, Figure 4 shows that the use of time adaptivity allows one to significantly improve the performance of the proposed processing when the beams are formed in the jammer DOAs, for powerful jammers seen in distant sidelobes. Then, we observe that the choice of a second normalized Doppler frequency close to that of the target one seems adequate. On the contrary to the case where the second beam is formed in the jammer DOA, we observe no improvement of SINR due to the use of time adaptivity when an orthogonal beam is used (with $\theta_2 = 1.9$ deg.).

Finally, based on the analysis performed in this Section, we make the following concluding remarks:

- Beamforming in the jammer DOAs leads to performance which degrade with antenna rotation
- Those performance losses can be compensated by use of time adaptivity, but the resulting SINR is very dependent on the choice of the Doppler filters normalized frequencies
- Beamforming with orthogonal beams at small DOAs leads to non optimal but robust performance w.r.t. antenna rotation
- Those performance losses are not significantly compensated by use of time adaptivity

5. SIMULATIONS

We now perform Monte Carlo simulations to compare the performance of different space-time processings. We assume that four jammers of DOAs -20, -17, 10 and 18 deg. and power $\sigma_J^2 = 30$ dB are present, as well as clutter reflectors between -20 and 20 deg. with density 1pt/deg. and power by reflector $\sigma_c^2 = 11$ dB. For BDSTAP, five beams are formed. The first one is always formed in the target DOA. The other ones are either in the jammers DOAs or orthogonal beams with DOAs in $[-3.8, -1.9, 1.9, 3.8]$ deg. When used for BDSTAP, the second normalized Doppler frequency for the processing is $f_2 = 0.15$. In Figure 5, we compare BDSTAP algorithm with different parameters with the standard motionless ground-based radar space-time processing and with a typical RR-STAP algorithm. The standard ground-based radar processing consists in making Doppler filtering on each sensor and then making space adaptive filtering. The latter processing is made by use of LSMI (Loaded Sample Matrix Inversion [12]) algorithm which allows one to make the estimated covariance matrix inversible when less samples than the number of sensors are used. To distinguish this processing from STAP, it will be called TPSAP (Time Processing Space Adaptive Processing). The chosen RR-STAP algorithm is the EVP (EigenVector Projection [6]) for which we assume that the interference subspace dimension is known to compute the filter. First, we test the influence of antenna rotation on the normalized SINRs of the different algorithms. The interference subspace dimension is here equal to 60.

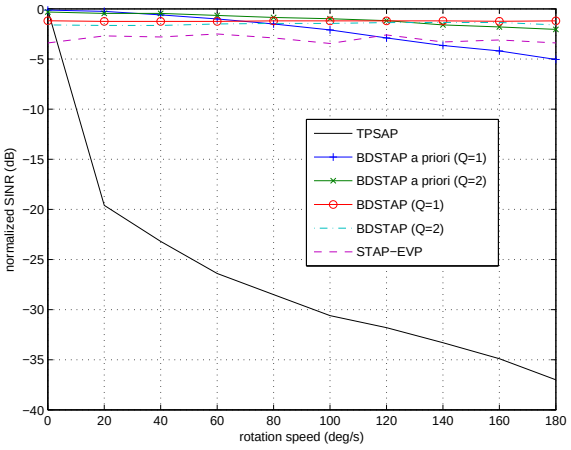

Figure 5 - Normalized SINR of the different STAP algorithms as a function of ω

Primarily, we observe that TPSAP algorithm rapidly degrades when the antenna rotates. It can be explained by two reasons. First, the rotation leads to affecting a non-zero Doppler frequency, sensor-dependent, to clutter components. Therefore, clutter mitigation is degraded. Then, making Doppler processing before space filtering leads to a spectral leakage of the jamming covariance matrix when the antenne rotates, according to [13]. Therefore, jamming mitigation is also degraded. Secondly, we note that STAP-EVP algorithm is robust to antenna rotation but has performance limited by a low convergence speed (depending on the dimension of the interference subspace, according to [8]). Here, the number of samples is twice the interference subspace dimension, and therefore the normalized SINR is approximately equal to -3 dB. Finally, at small rotation speeds, BDSTAP algorithm with the considered parameters leads to better performance than the STAP-EVP and the TPSAP algorithms. At speeds lower than 70 deg/s, BDSTAP with beams formed in the jammer directions (called BDSTAP a priori) with $Q = 1$ and $Q = 2$ lead to the best performance in terms of SINR. However, when the rotation speed increases, we observe a decrease of SINR, significant for $Q = 1$ and limited for $Q = 2$. With high rotation speeds, the best performance are obtained by use of BDSTAP with orthogonal beams and $Q = 1$.

Next, in order to compare the convergence speed of BDSTAP and STAP-EVP algorithms, we now analyze the influence of the number of samples used for computation of adaptive filters. We thus plot in Figure 6 the SINRs as a function of K for STAP and BDSTAP algorithms with different values of Q. The rotation speed is set to 180 deg/s.

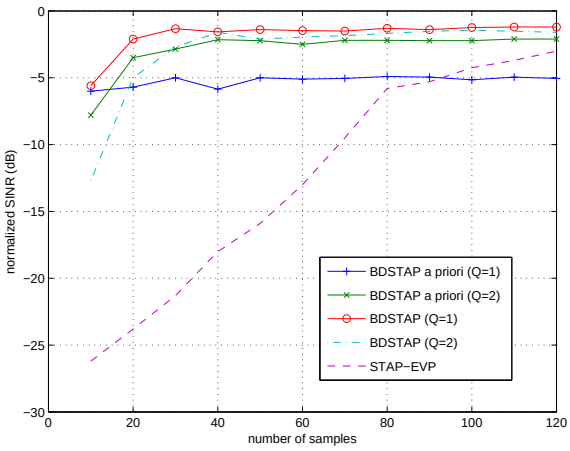

Figure 6 - Normalized SINR of the different STAP algorithms as a function of K

We observe that BDSTAP algorithms converge more rapidly than STAP-EVP. This is explained by the reduced dimension of data for BDSTAP (equal to $PQ = 5$ or $PQ = 10$), respectively for $Q = 1$ and $Q = 2$, instead of the rank equal to 60 of the reduced-rank covariance matrix for STAP-EVP. Except, for BDSTAP with beams formed in the jammers DOAs with $Q = 1$, we note that the SINR after BDSTAP algorithm is greater than after STAP-EVP algorithm even with an high number of samples.

6. CONCLUSION

In this paper, we have proposed the use of beamspace post-Doppler STAP in the context of ground-based rotating radar systems without jamming alone reference. After having detailed the principle of the algorithm, we have given design rules for its implementation, based on a performance analysis. Finally, we have shown by simulations that the proposed processing was robust to antenna rotation and has the advantage over other STAP algorithms of a good convergence speed and a reduced implementation complexity.

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