RANGE RECURSIVE SPACE TIME ADAPTIVE PROCESSING (STAP) FOR MIMO AIRBORNE RADAR

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ABSTRACT

This paper presents a range recursive algorithm for the space time adaptive processing (STAP) of multi input multi output (MIMO) airborne radar signals involved in clutter rejection for the detection of slow moving ground targets. The MIMO aspect comes from the fact that the transmitter consists of an array of spaced elements sending non coherent waveforms and that the receiver is a conventional array used for spatial clutter rejection. The transposition of the STAP algorithms from the single input multi output (SIMO) systems to the MIMO ones has been claimed to theoretically improve performance in clutter resolution and rejection. However, even if this transposition is conceptually easy, in practice, the convergence and the computational complexity of the MIMO-STAP algorithms are higher than for SIMO models. After reconsidering the advantages and drawbacks of the extended MIMO-STAP, namely the sample matrix inversion (SMI) and eigencanceller (EC) algorithms, we propose the fast approximated power iteration (FAPI) range recursive algorithm as an alternative to resolve the convergence and complexity problems

1. INTRODUCTION

Space time adaptive processing (STAP) of airborne radar signals received on an array of antennas consists in constructing for each range and in each look direction a Doppler filter capable of rejecting ground clutter in order to detect a possible slow moving target [1][2][3]. In conventional STAP, the target and the ground are illuminated by a known waveform coming from a single omnidirectional transmitter antenna localized (monostatic configuration) or not (bistatic) on the same platform as the receiver antenna array.

It has been recently shown that multiple-input multiple-output (MIMO) antenna systems have the potential to improve the performance of communication and radar systems over single-input multiple-output (SIMO) systems [4][5][6]. Concerning STAP, it has been claimed that the clutter rejection and consequently target detection may be improved by considering, instead of a single omnidirectional transmitter antenna, an array with spaced antenna elements sending non coherent (possibly orthogonal) waveforms. After their reflection on the ground and the eventual target they can then be extracted at the receiver by a matched filters bank [7][8][9]. Indeed, it has been shown that for certain configurations and geometries of radar antenna arrays at the transmitter and the receivers, the transposition of STAP algorithms, well established in the literature, from SIMO to MIMO yields as if STAP would be applied to a SIMO system with a virtual array of larger size (equal to the product of the numbers of transmitter and receiver elements) thus involving a higher resolution of the clutter spectrum [9]. However this improvement is obtained at the price of an increased computational load and a slower convergence of the algorithms.

In this paper we will first explain the transposition of the sample matrix inversion (SMI) [10] and the eigencanceller (EC) [11] based STAP algorithms from SIMO to MIMO radar systems and we will discuss the actual advantages and drawbacks of the MIMO extension. We will then propose a MIMO extension of a range recursive STAP algorithm showing that it can reach the performance of the EC algorithm, namely the same convergence advantage over the SMI, related to the rank of the clutter covariance matrix, with a drastically reduced computational complexity.

The paper is organised as follows. Next section is devoted to the presentation of the MIMO signal model received at the receiver for the STAP approach. Section 3 will shortly recall the SMI and EC STAP algorithms in order to detail the actual advantages and drawbacks of their extension to the MIMO case. In section 4, the extension of the fast approximated power iteration (FAPI) range recursive STAP algorithm [12][13] to MIMO STAP will be presented and its advantages over the EC algorithm will be established. The previous discussion and results will be supported by simulations in section 5. Section 6 is the conclusion.

2. SIGNAL MODEL

Consider the simplified MIMO narrowband airborne radar system of Figure 1[1] with transmitting and receiving antennas arranged in two collocated uniform linear arrays (ULA) of M and N elements, respectively [9]. The system transmits

[1] For simplifications, the scheme and the corresponding model assume that the target, the ground clutter and the antenna array are coplanar. In fact the problem is 3D and in our simulations, each look direction is of course parameterized by both elevation and azimuth angles.

simultaneously M linearly independent (orthogonal) waveform baseband pulses $\Phi_m(\tau)$, τ denoting time within a radar pulse interval of length T. The transmitted signals of the m-th antenna corresponding to the l-th pulse interval among L pulses in a coherent processing interval (CPI) can be expressed as

$$s_m(lT+\tau) = \sqrt{E}\Phi_m(\tau)e^{j2\pi f(lT+\tau)}$$

where m=1, 2,…, M, f is the carrier frequency and E is the transmitted energy of the pulse. The signals after their reflection on a target or on a ground clutter patch in direction θ can be extracted on each receiver by M matched filters. The transmitter and the receiver are assumed close enough and on the same platform so that they share the same angle θ. The radar platform is flying at altitude h with a velocity vector **v** assumed collinear with the x-axis radar and of amplitude v. This configuration is referred to as the side looking (SL) configuration. We here assume a non ambiguous clutter and the absence of jammer and internal clutter motion (ICM). Because of the orthogonality of the transmitted waveforms, the extracted signal at the output of the m-th matched filter at the n-th receiving antenna and corresponding to the l-th pulse is given by $x_{n,m,l} = x^t_{n,m,l} + x^c_{n,m,l} + x^n_{n,m,l}$ where the target (if it exists at this range) and clutter respective components can be expressed by

$$x^t_{n,m,l} = \rho_t e^{j\frac{2\pi}{\lambda}(\sin\theta_t(2vTl+d_R n+d_T m)+2v_t Tl)}$$

$$x^c_{n,m,l} = \sum_{i=0}^{N_c-1}\rho_{c,i}e^{j\frac{2\pi}{\lambda}\sin\theta_{c,i}(2vTl+d_R n+d_T m)}$$

where θ_t, ρ_t and $\theta_{c,i}$, $\rho_{c,i}$ are the looking direction and the amplitude of the reflected signals associated with the target and the i-th clutter patch, respectively. N_c is the number of clutter patches at a given range, v_t is the target speed relative to the platform, d_R and d_T are the transmitting and receiving antennas spacing respectively, and λ is the wavelength. $x^n_{n,m,l}$ is a white Gaussian noise component. Let us define the normalized spatial and Doppler frequencies such as $f_{S,t} = d_R\sin\theta_t/\lambda$, $f_{S,i} = d_R\sin\theta_{c,i}/\lambda$, $f_{D,t} = 2T(v\sin\theta_t + v_t)/\lambda$ and $f_{D,i} = 2Tv\sin\theta_{c,i}/\lambda$, for the target and the i-th clutter patch, respectively. In order to avoid spatial aliasing, $d_R = \lambda/2$ is assumed and $\gamma = d_T/d_R$ and $\beta = 2vT/d_R$ are defined. With these notations the target and clutter components of the extracted signals can be rewritten as

$$x^t_{n,m,l} = \rho_t e^{j2\pi f_{S,t}(n+\gamma m)}e^{j2\pi f_{D,t}l}$$

$$x^c_{n,m,l} = \sum_{i=0}^{N_c-1}\rho_{c,i}e^{j2\pi f_{S,i}(n+\gamma m+\beta l)}$$

There is thus a total of NML extracted signals at the receiver output during a CPI and for a given range, which can be viewed as the signals which would be received on a virtual array of NM antennas in a SIMO radar system whereas only N+M physical antennas exist. By stacking the MNL MIMO STAP signals in a MNL dimensional vector **x** yields

$$\mathbf{x} = \mathbf{x}^t + \mathbf{x}^c + \mathbf{x}^n \quad (1)$$

with
$$\mathbf{x}^t = \rho_t\mathbf{b}(f_{D,t})\otimes\mathbf{a}_R(f_{S,t})\otimes\mathbf{a}_T(f_{S,t}) \quad (2)$$

$$\mathbf{x}^c = \sum_{i=1}^{N_c}\rho_{c,i}\mathbf{b}(f_{D,i})\otimes\mathbf{a}_R(f_{S,i})\otimes\mathbf{a}_T(f_{S,i}) \quad (3)$$

where $\mathbf{b}(.)$, $\mathbf{a}_R(.)$ and $\mathbf{a}_T(.)$ are temporal and receiving and transmitting spatial steering vectors of dimensions L, N and M, respectively. $\otimes$ denotes the Kronecker product. The p-th components of the steering vectors are $b_p(f_D) = e^{j2\pi f_D\beta p}$, $a_{R,p}(f_S) = e^{j2\pi f_S p}$ and $a_{T,p}(f_S) = e^{j2\pi f_S\gamma p}$, with p=0,…,L-1, p=0, …, N-1 and p=0, …, M-1, respectively.
Let us recall that in the case of SIMO, the target and clutter components would reduce to the following expressions

$$\mathbf{x}^t = \rho_t\mathbf{b}(f_{D,t})\otimes\mathbf{a}_R(f_{S,t})$$

$$\mathbf{x}^c = \sum_{i=1}^{N_c}\rho_{c,i}\mathbf{b}(f_{D,i})\otimes\mathbf{a}_R(f_{S,i})$$

where $\mathbf{x}^t$ and $\mathbf{x}^c$ would be vectors of dimension NL.

3. THE MIMO SMI AND EC ALGORITHMS

The aim of STAP is to mitigate the effects of ground clutter in order to detect an eventual slowly moving target. This is performed by a two dimensional filtering of the received data followed by a detector. The optimal STAP weight vector maximizing the signal to noise plus interference ratio (SINR) [10] is given by

$$\mathbf{w}_{opt} = \alpha\mathbf{R}^{-1}\mathbf{x}^t \quad (4)$$

where α is a scalar constant which does not affect the SINR and $\mathbf{R}$ is the clutter plus noise covariance matrix

$$\mathbf{R} = \mathrm{E}[(\mathbf{x}^c + \mathbf{x}^n)(\mathbf{x}^c + \mathbf{x}^n)^{\mathrm{H}}] \quad (5)$$

The output of the filter is $\mathbf{r} = \mathbf{w}^H_{opt}\mathbf{x}$.
The extension from the SIMO to the MIMO system is trivial, matrix $\mathbf{R}$ and weight vector $\mathbf{w}_{opt}$ being of dimension MNLxMNL and MNLx1 in the latter case instead of NLxNL and NLx1 in the first case, respectively.
It is well known that the localization of sources by an antenna array is improved when the number of receiving elements of the array increases. In the case of MIMO STAP, a better estimation of the clutter spectrum is thus expected yielding a better rejection of it when constructing the weight vector (4). Indeed, in this case, it has been seen that the number of elements is virtually MN for a number of physical elements of N+M instead of N in the case of SIMO. However this is only true in the theoretical (optimal) case.

In practice, neither $\mathbf{R}$ or $\mathbf{x}^t$ are known. $\mathbf{R}$ may be estimated from K secondary snapshots $\mathbf{x}(k)$ around the range cell under test k_0 as follows

$$\hat{\mathbf{R}}(k_0) = \frac{1}{K-1}\sum_{\substack{k=1\\k\neq k_0}}^{K}(\mathbf{x}^c(k)+\mathbf{x}^n(k))(\mathbf{x}^c(k)+\mathbf{x}^n(k))^{\mathrm{H}} \quad (6)$$

The target component $\mathbf{x}^t$ is replaced by a steering vector of the form $\mathbf{v}(f_D, f_S) = \mathbf{b}(f_D)\otimes\mathbf{a}_R(f_S)\otimes\mathbf{a}_T(f_S)$ computed for a candidate couple of Doppler and spatial frequencies (f_D, f_S). The suboptimal sample matrix inversion (SMI) STAP weight vector then consists in [1-3]

$$\mathbf{w}_{SMI}(k_0, f_D, f_S) = \hat{\mathbf{R}}(k_0)^{-1}\mathbf{v}(f_D, f_S) \quad (7)$$

Note that a weight vector is computed for each range cell and each couple of Doppler and spatial frequencies.

It is known in the STAP literature [14] that the "convergence" of the SMI defined as the number of snapshots necessary to achieve a SINR loss performance of 3 dB compared to the optimal STAP in the absence of clutter, is twice the dimension of the received vector. It follows that the convergence for the SIMO and the MIMO cases is obtained for K=2NL and K=2NML snapshots, respectively. In the same way, the larger the size of the covariance matrix, the more complex the computational load required for the inversion in (7). It follows that $O((MNL)^3)$ and $O((NL)^3)$ are necessary to compute the SMI weight vectors in the MIMO and SIMO cases, respectively. The theoretical interest of the MIMO system becomes thus limited in practice.

An alternative approach proposed in the literature for reducing the convergence is based on rank reduction. For example, the eigencanceller (EC) method consists in computing the STAP weight vector as follows

$$\mathbf{w}_{EC}(k_0, f_D, f_S) = \left(\mathbf{I} - \mathbf{U}_c\mathbf{U}_c^H\right)\mathbf{v}(f_D, f_S) \quad (8)$$

Indeed, the clutter covariance matrix being rank deficient the clutter plus noise covariance matrix $\mathbf{R}$ can be eigendecomposed as follows

$$\mathbf{R} = \mathbf{U}_c\mathbf{\Lambda}_c\mathbf{U}_c^H + \sigma_n^2\mathbf{U}_n\mathbf{U}_n^H \quad (9)$$

In practice, this eigendecomposition is obtained from the estimated covariance matrix (6) yielding a convergence as above defined of K=2r where r is the rank of the clutter covariance matrix. It has been shown in [3], and the references inside, and in [9] that the rank in the SIMO and the MIMO cases is approximately

$$r_{SIMO} = N + \beta(L-1)$$

and

$$r_{MIMO} = N + \gamma(M-1) + \beta(L-1)$$

in the absence of jammers. It is thus worth noting that the convergence speed is no longer proportional to the product of the number of transmitting and receiving elements but a linear combination of them. Moreover it is also worth noting that if you compare a SIMO antenna array of $N'=MN$ physical elements you can find a MIMO system of N and M physical receiving and transmitting elements, so that by choosing adequately γ ($\gamma < N$) the rank r_{MIMO} is smaller than the rank r'_{SIMO} of the corresponding SIMO. It then follows that with the EC approach, the MIMO STAP system can converge faster than its SIMO counterpart. This was not the case for the SMI algorithm.

From the computational complexity point of view the EC STAP algorithm encounters the same drawbacks as the SMI algorithm, it is to say that it is increased by a multiplicative factor of $O((M)^3)$ because of the eigendecomposition of the clutter plus noise covariance matrix. It is why in the following section we propose a range recursive EC-based STAP algorithm. It takes benefit of the abovementioned rank reduction property and consequently converges faster than the SMI and has a computational load of only $O(NL)$ and $O(MNL)$ for the SIMO and the MIMO cases, respectively.

4. RANGE RECURSIVE FAPI ALGORITHM

Here we propose to use a range recursive subspace-based algorithm in order to construct the STAP filter.

Traditionally used in spectral analysis and antenna processing as time-recursive adaptive algorithms [12], adaptive recursive subspace-based algorithms such as FAPI have been more recently used in STAP for airborne radar [13][2]. In this case of STAP, the recursion relates to the distance instead of time.

The classical subspace tracking algorithm on which FAPI is established considers the following scalar function [15]

$$J(\mathbf{W}) = E\left(\left\|\mathbf{x} - \mathbf{W}\mathbf{W}^H\mathbf{x}\right\|^2\right)$$

where $\mathbf{x}$ is the observed data vector of covariance matrix $\mathbf{R}$ and $\mathbf{W}$ is the matrix argument. This cost function possesses just a global minimum [15] which is attainted only if $\mathbf{W} = \mathbf{U}_c\mathbf{Q}$ where $\mathbf{U}_c$ the clutter subspace basis defined in (9) and Q is is a unitary matrix. The original algorithm which considered this abovementioned criterion is the projection approximation subspace tracking (PAST) algorithm [15] replacing the expectation by an exponentially weighted sum and supposing an approximation of the clutter subspace ($\mathbf{W}(i-1) \approx \mathbf{W}(i)$ where i was time in the original version of PAST and that we transpose to range in the proposed STAP version). Thus a basis of the clutter subspace is obtained as the solution of the unconstrained minimization problem:

$$J(\mathbf{W}(k)) = \sum_{i=1}^{k}\beta^{k-i}\left\|\mathbf{x}(i) - \mathbf{W}(k)\mathbf{W}(i-1)^H\mathbf{x}(i)\right\|^2$$

where $\mathbf{x}(i)$ is the observed data vector at range i and $\mathbf{W}(k)$ is the estimated interference (clutter plus noise) subspace basis at range k and β a forgetting factor, $0<\beta<1$. This exponentially least square problem is solved by a recursive computa-

[2] Range or time recursive subspace-based algorithms are not only devoted to subspace tracking in case of non stationarity but also to converge towards a stationary optimal or suboptimal solution with a smaller computational complexity than their block counterparts.

tion. We here are more interested by the FAPI algorithm [13] which is based on the previous approach with a less restrictive approximation: the projection on the clutter subspace at range i is approximated by the projection on the clutter subspace at range $i-1$.

$$\mathbf{W}(i)\mathbf{W}(i)^H \approx \mathbf{W}(i-1)\mathbf{W}(i-1)^H$$

The obtained subspace is found to be orthonormalized. The details of this algorithm are given in table 1. The corresponding STAP filter computed for each snapshot is obtained through

$$\mathbf{w}_{FAPI}(k) = (\mathbf{I} - \mathbf{W}(k)\mathbf{W}(k)^H)\mathbf{v}(f_D, f_S) \quad (10)$$

Table 1 FAPI Algorithm

<u>**Initialization :**</u> $\mathbf{W}(0) \leftarrow \mathbf{I}_{M\times N}$, $\mathbf{Z}(0) \leftarrow \mathbf{I}_{N\times N}$

for $k = 1$ to Nbr snapshot **do**

$\mathbf{y}(k) = \mathbf{W}(k-1)^H \cdot \mathbf{x}(k)$

$\mathbf{h}(k) = \mathbf{Z}(k-1) \cdot \mathbf{y}(k)$

$\mathbf{g}(k) = \frac{\mathbf{h}(k)}{\beta + \mathbf{y}^H(k)\cdot\mathbf{h}(k)}$

$\mathbf{e}(k) = \mathbf{x}(k) - \mathbf{W}(k-1)\cdot\mathbf{y}(k)$

$\varepsilon^2(k) = \|\mathbf{x}(k)\|^2 - \|\mathbf{y}(k)\|^2$

$\tau(k) = \frac{\varepsilon^2(k)}{1+\varepsilon^2(k)\|\mathbf{g}(k)\|^2 + \sqrt{1+\varepsilon^2(k)\|\mathbf{g}(k)\|^2}}$

$\eta(k) = 1 - \tau(k)\,\|\mathbf{g}(k)\|^2$

$\mathbf{y}'(k) = \eta(k)\mathbf{y}(k) + \tau(k)\mathbf{g}(k)$

$\mathbf{h}'(k) = \mathbf{Z}(k-1)^H\mathbf{y}'(k)$

$\epsilon(k) = \frac{\tau(k)}{\eta(k)}(\mathbf{Z}(k-1)\mathbf{g}(k) - (\mathbf{h}'(k)\mathbf{g}(k))\mathbf{g}(k))$

$\mathbf{Z}(k) = \frac{1}{\beta}(\mathbf{Z}(k-1) - \mathbf{g}(k)\mathbf{h}'(k)^H + \epsilon(k)\mathbf{g}(k)^H)$

$\mathbf{e}'(k) = \eta(k)\mathbf{x}(k) - \mathbf{W}(t-1)\mathbf{y}'(k)$

$\mathbf{W}(k) = \mathbf{W}(k-1) + \mathbf{e}'(k)\cdot\mathbf{g}(k)^H$

end for

In table 1, the input $\mathbf{x}(k)$ is $\mathbf{x}$ defined in (1) at range k.

5. SIMULATION RESULTS

In this section, we compare the performance of our proposed FAPI method, the SMI and EC in the MIMO context of N=12 receiving elements, M=3 transmitting elements and L=10 pulses, β=1 and γ=10 or 2. The performance measure is here defined as the signal to interference plus noise ratio loss (SINR loss) defined as the ratio of the SINR to the SNR (without clutter)

$$SINR_{loss} = \frac{\sigma^2 \left| \mathbf{w}^H \mathbf{v}(f_D, f_S) \right|^2}{NML\ \mathbf{w}^H \mathbf{R}\mathbf{w}} \quad (11)$$

where $\mathbf{w}$ is the weight vector of the clutter rejection filter calculated according to each algorithm (7), (8) or (10).

For the simulations, a pulsed Doppler airborne monostatic radar composed of a uniform linear array in a side looking configuration is considered. The operating frequency of the radar is 450 MHz with a PRF of 600 kHz. The radar bandwidth is 4.5 MHz. The platform is assumed to move with a constant velocity of 100 m.s^{-1} at the altitude of 9km. The clutter to noise ratio (CNR) is assumed equal to 30 dB. The SINR loss is plotted for f_S=0 as a function of the normalized Doppler frequency f_D.

Figure 2 exhibits the results concerning the SIMO case with a single transmitting antenna (M'=1) and a receiving antenna array of $N'=ML$ physical elements. Here only K=120 snapshots are used in (6) to estimate the clutter plus noise covariance matrix. In this case, NML=360 and the SMI should require at least 720 snapshots to converge according to the abovementioned definition. The rank being $r_{SIMO} = 45$ the rank reduction based algorithms, namely the EC and FAPI, are capable of converging with at least 90 snapshots. This is observed in Figure 2. Let us note that FAPI algorithm performs similarly to EC algorithm (with a drastically reduced complexity).

Figure 3 exhibits the results concerning the MIMO case with transmitting and receiving antenna arrays of M=3 and N=12 physical elements, respectively. K=120 snapshots are used as in the previous case and γ=**10.** We can see that the results are comparable to those of the SIMO case (Figure 1). It is to say that the MIMO STAP behaves with a total of only $M+N$=15 physical elements as a SIMO STAP system with a virtual array of N'=36 receiving elements. Note that in this case the rank is $r_{MIMO} = 41$, smaller than that of the corresponding SIMO system.

In Figure 4, the performance of the SIMO and MIMO versions of the EC and FAPI algorithms are compared in the same conditions that those of Figures 2 and 3 except that K=60 snapshots and γ=**2.** In this case, the rank for the SIMO case is still equal to 45 while for the MIMO case it is reduced to r_{MIMO}=25. It is why we can observe that there are enough snapshots for MIMO EC and MIMO FAPI to converge (a little bit more than twice the rank, it is to say, at least 50 snapshots) while there are not enough snapshots for the SIMO EC and FAPI algorithms (where at least 90 snapshots are required).

6. CONCLUSION

This paper proposes the FAPI STAP algorithm as an alternative to the EC STAP algorithm in the context of MIMO radar systems for clutter rejection and target detection. Indeed, while being a reduced rank subspace based technique as the EC algorithm, it requires much less training snapshots to converge than the SMI method. Contrarily to the EC it also has a low computational cost which is a linear function (instead of a cubic function) of the dimension of the virtual received signal vector. Note that the FAPI STAP algorithm for the MIMO context could be used to track clutter range non stationarities. As a perspective, the case of a transmitter and a receiver not localized on the same platform as well as non orthogonal waveform pulses could also be of interest.

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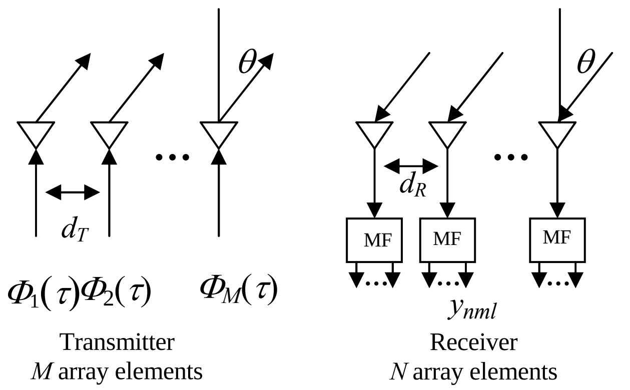

Figure 1– Simplified scheme of a MIMO radar system

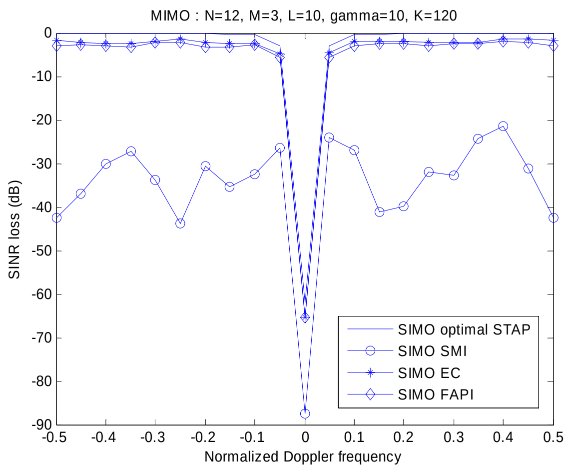

Figure 3 – SINR loss for the MIMO STAP algorithms with *N=12, M*=3, *L*=10, γ =10, K=120 snapshots.

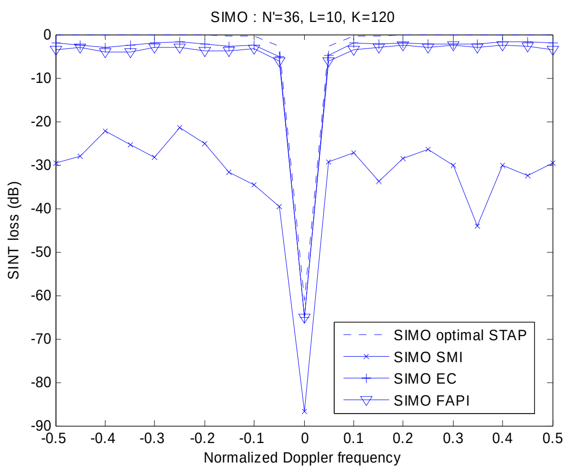

Figure 2 – SINR loss for the SIMO STAP algorithms with *N'=NM*=36, *L*=10, K=120 snapshots.

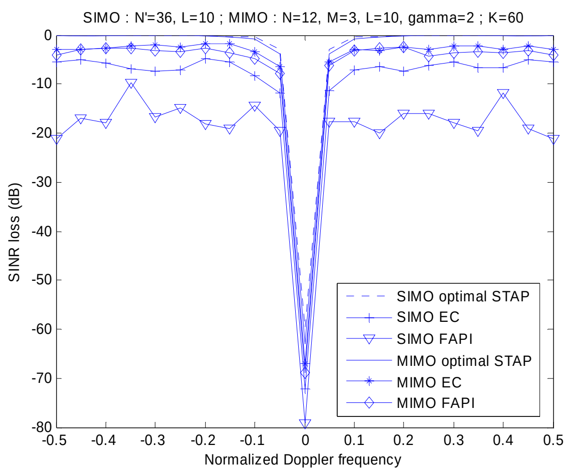

Figure 4 – Comparison of the MIMO and SIMO EC and FAPI STAP algorithms with *N=12, M*=3, γ =2, *N'*=36, *L*=10, *K*=60.