BISTATIC STAP USING DVB-T ILLUMINATORS OF OPPORTUNITY

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Abstract

In this paper, we examine the feasibility of applying Space-Time Adaptive Processing (STAP) to bistatic passive radars using noise-like signals in general and Digital Video Broadcasting-Terrestrial (DVB-T) illuminators of opportunity in particular. We show that by working on the appropriate mixing product, we make the application of classical STAP methods and nonhomogeneity detection possible. We finally confirm these theoretical results by simulations created from real measurements.

1 Introduction

Passive bistatic radars offer definitive advantages [13] such as low cost, low weight and enhanced radar cross-section for certain geometries. Moreover, these systems are totally undetectable since the receiver is totally passive.

Several illuminators of opportunity like FM radio broadcast [21], satellites [8,4], digital video broadcast (DVB-T) [16], and Global System for Mobile communications (GSM) base stations [18,10] have already been studied in the case of a fixed receiver.

DVB-T transmitters are interesting because of their ubiquitous spatial coverage. Moreover, they are permanent in time and their equivalent isotropic radiated power can reach 40 to 50 dBW. In addition, signals exhibit a thumbtack like ambiguity function due to the noise-like behaviour of the orthogonal frequency-division multiplexing (OFDM) modulation used [5], and their bandwidth (7,61 MHz, for the 8K mode) leads to a range resolution of about 20m making it much more interesting than GSM signals [14].

STAP is typically used to filter out (clutter-) interferences in ground moving target indicator (GMTI) radars in order to detect slow-moving targets. This processing consists in performing a joint spatio-temporal optimum filtering of the signal in order to reject interferences [9, 7].

In the STAP literature, it is assumed that the available signal is formed by the echoes from a pulse-Doppler radar. This paper shows how STAP can be applied to other noise-like signals and in particular to the DVB-T signals.

Part 2 shows how these signals must be processed.

Part 3 deals with the estimation of the covariance matrix required to perform STAP through the use of two of the most classical methods : the Principal Components (PC) method and the Joint Domain Localized (JDL) method.

Part 4 is linked to the improvement of the estimation due to the rejection of range cells where nonhomogeneities have been detected.

Part 5 finally depicts results on simulated STAP data created from real DVB-T signals.

2 Generalization of STAP to noise-like signals

Let us consider a reference signal x_{ref} delivered by an illuminator of opportunity. This signal, coming from the direct path, can be obtained, in the case of OFDM signals, using pilot-aided channel estimation.

x_{ref} will create a spatio-temporal signal x, containing echoes from the potential targets, the clutter, and the direct path signal. x is received by an array antenna made of N_s elements, during a coherent integration time T_{ci} corresponding to N_d samples.

n denotes the range at which the correlation is computed, $\nu_s = \frac{d \sin\theta}{\lambda}$ is the reduced spatial frequency with d the inter-element spacing, λ the carrier wavelength and θ the incidence angle. $\nu_d = \frac{f_d S}{f_s}$ is the reduced Doppler frequency with f_d the Doppler frequency of the target, S the subsampling factor and f_s the sampling frequency of the acquisition.

The range-Doppler diagram of the waveform associated to the signal x [11,3] :

$$\chi(n,\nu_d)=\sum_k x(k)x^*_{ref}(k-n)e^{-j2\pi\nu_d k} \qquad (1)$$

can be generalized to the range-space-Doppler diagram :

$$\chi(n,\nu_s,\nu_d)=((x_{ref}\otimes c_{N_s})\circ s)^\dagger x \qquad (2)$$

where c_{N_s} is a $N_s\times 1$ column vector with unit elements, $\otimes$ the Kronecker product and $\circ$ the Hadamard (element-wise) product. s is the spatio-temporal steering vector :

$$s=s_s(\nu_s)\otimes s_d(\nu_d) \qquad (3)$$

In the case of an uniform linear array (ULA), the spatial steering vector is :

$$s_s(\nu_s)=\left[1\ e^{j2\pi\nu_s}\ \ldots\ e^{j2\pi\nu_s(N_s-1)}\right]^T \qquad (4)$$

The temporal steering vector is given by :

$$s_d(\nu_d)=\left[1\ e^{j2\pi\nu_d}\ \ldots\ e^{j2\pi\nu_d(N_d-1)}\right]^T \qquad (5)$$

The equation (2) can also be written :

$$\chi(n,\nu_s,\nu_d)=s^\dagger x_m \qquad (6)$$

x_m is the mixing product resulting from mixing the signal from each channel with a time-delayed version of the reference. This operation allows to face the fact that, for noise-like signals, the temporal phase shift from a sample to an other is not only due to the Doppler frequency but also to the signal itself.

Since the targets of interest induce Doppler frequencies that are much smaller than the sampling frequency, the signal x_m can be low-pass filtered and subsampled as suggested in [17]. Note that this subsampling does not affect the range resolution of the radar.

It is interesting to consider the spatio-temporal steering vector in equation (6) as the weighting vector able to reject additive white Gaussian noise.

The optimization of the signal to interference plus noise ratio (SINR) leads to the output of the adaptive filter :

$$y=w_m{}^\dagger x_m \qquad (7)$$

where the weighting vector :

$$w_m=R_m{}^{-1}s \qquad (8)$$

rejects the interferences and the noise in an optimum way [9,20].

R_m is the covariance matrix of the interference plus noise mixed data.

3 Estimation of the interference covariance matrix

The interference covariance matrix R_m required to compute the optimum filter (8) is defined as :

$$R_m=E\left[x_{m_{i+n}}x^\dagger_{m_{i+n}}\right] \qquad (9)$$

where $x_{m_{i+n}}$ is the mixed, low-pass filtered, and subsampled signal, containing only interference and noise.

The expectation operator E is typically replaced by a sum over data samples taken at different ranges [15], i.e. the sample covariance matrix (SCM).

The estimation obtained will be unbiased only if the averaged data samples are independent and identically distributed.

In bistatic configurations, the clutter power spectrum locus is known to generally exhibit a range-dependency. Hence, independently of possible clutter nonhomogeneities, the conditions for unbiased estimation are typically not verified. However, in the configuration considered here, i.e. a static transmitter and a side-looking receiving antenna, it was shown that the clutter power spectrum locus is independent of the range.

This means that in the considered configuration, no geometry-induced range dependence of the clutter statistics will be present.

The low-rank nature of R_m can be exploited to further reduce the number of samples required to perform a useful estimation. In particular, a method based on the extraction of its principal components (PC) was proposed [6] and can still be applied.

This method is a signal (steering vector) independent but data dependent method.

Figure 1 shows the relative importance of the different eigenvalues of R_m and the possibility to apply diagonal loading (DL) leading to PC+DL method.

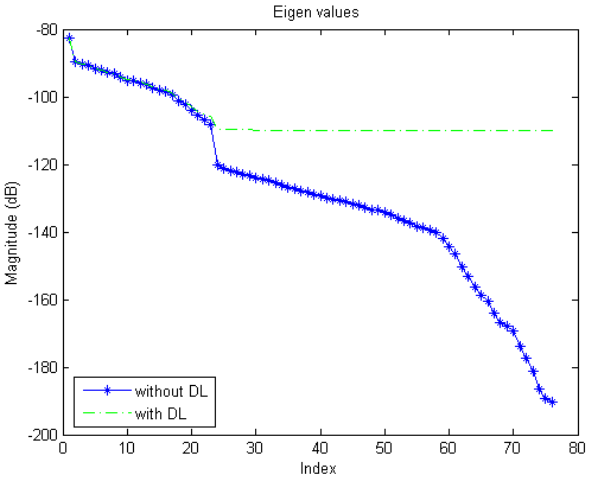

Figure 1 : PC eigenvalues and diagonal loading.

The possibility to detect an echo, created by a DVB-T transmitter among the direct path, clutter and nonhomogeneities and using PC+DL method is illustrated by figures 2 and 3 (part 5).

The second kind of method successfully implemented in this study is a signal dependent but data independent one : the Joint Domain Localized (JDL) method.
Wang and Cai [19] introduced the algorithm associated to this method which adaptively processes the radar data after transformation to the angle-Doppler domain. The transformation matrix T is :

$$T = T_d \otimes T_s \tag{10}$$

with

$$T_d = \left[s_d(\nu_{d_{-1}}) \; s_d(\nu_{d_0}) \; s_d(\nu_{d_{+1}}) \right] \tag{11}$$

and

$$T_s = \left[s_s(\nu_{s_{-1}}) \; s_s(\nu_{s_0}) \; s_s(\nu_{s_{+1}}) \right] \tag{12}$$

This adaptive processing is restricted to a localized processing region, around the direction (ν_{d_0}, ν_{s_0}), which allows to reduce significantly the required sample support and computation load. This improvement is due to the reduction of the size of the covariance matrix from $N_s N_d \times N_s N_d$ to $\eta_s \eta_d \times \eta_s \eta_d$ where η_s and η_d are chosen equal to 3 in this case.

Figures 4 and 5, in part 5, illustrate the efficiency of this method in detecting a target even in a dense environment.

Although many other estimation methods exist, a complete discussion of covariance matrix estimation methods applicable in the current scenario is outside the scope of this paper and we will limit ourselves to the representative methods described above.

4 Non homogeneity detection (NHD)

Estimating the covariance matrix through training data is a key asset. The main risk is to be contaminated by non-homogeneities which don't share the same statistics than the interference in the range cell under test. Excising them can be achieved using several nonhomogeneity detectors linked to statistic test such as Generalized Inner Product (GIP) [12] or the statistic test associated with the Modified Sample Matrix Inverse (MSMI) [1,2]. The second one, which takes into account the steering vectors, will be preferred.
If we consider the look direction s, the test can be written

$$\Lambda_{MSMI} = \frac{\left| {w_m}^{\dagger} x_m \right|^2}{s^{\dagger} {R_m}^{-1} s} \tag{13}$$

Figure 6 shows the effective range localisation of the target C_1 and discrete non-homogeneities H_2 to H_5 using this test.

It is interesting to notice that the width of the statistic test can help us when choosing the number of adjacent range cells which are generally suppressed during the estimation. Choosing this number close to the width of the peak is the optimal choice whereas a smaller number will not allow to take into account the possible spread of the target in range. On the other hand, suppressing a larger number of adjacent range cells may prevent the process from taking advantage of some of the most representative (because close) cells.

5 End-to-end Results

STAP data used in this part have been simulated from real DVB-T signals. The configuration chosen is linked to further experimentations which should take place in 2007, involving a four-element, side-looking ULA antenna on a moving-platform. To illustrate the feasibility of the detection of targets in an OFDM signal where clutter and discrete nonhomogeneities are inserted at specific angle, Doppler and range cells it is interesting to both have a look at the output of adaptive filtering and the improvement factor (IF) :

$$IF = \frac{SINR_{output}}{SINR_{input}} = \frac{\dfrac{{w_m}^{\dagger} s s^{\dagger} w_m}{{w_m}^{\dagger} R_m w_m}}{\dfrac{s^t s}{trace(R_m)}} \tag{14}$$

The target and discrete nonhomogeneities are simulated by adding time-delayed and frequency-delayed versions of the reference signal to the signals from the spatial channels. The localisation of the various elements is defined as follow.

For the transmitter $(\nu_{s,T},\nu_{d,T})=(0.35,0.3)$, for the target C_1 $(\nu_{s,c_1},\nu_{d,c_1})=(-0.25,0.4)$, and for nonhomogeneities H_2 to H_5:

$$\nu_{s,H_i}=(0.4,0.1,-0.1,-0.4)$$
$$\nu_{d,H_i}=(-0,3,0.2,-0.2,-0.4)$$

The power of the target C_1 is 60dB bellow the one of the transmitter. The power of the nonhomogeneities is 20 to 40 dB above the power of C_1.

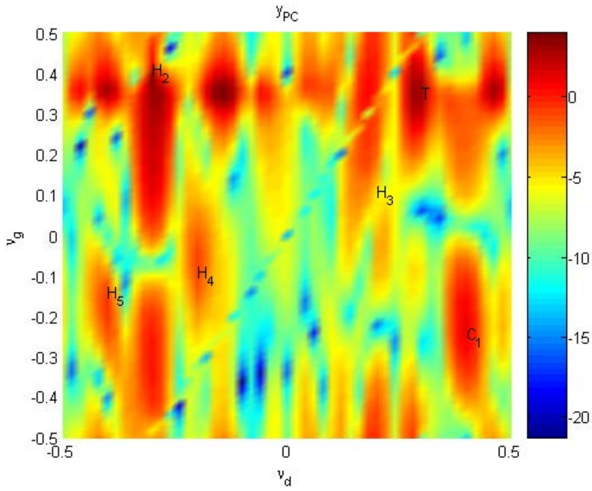

Figure 2: Output of the adaptive filter (PC method)

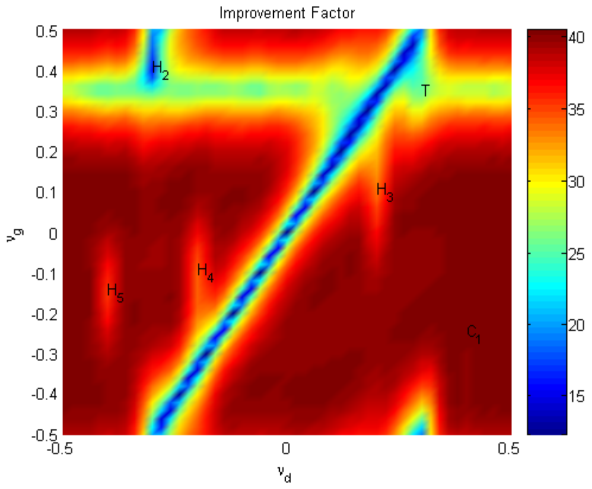

Figure 3: Improvement Factor (PC method)

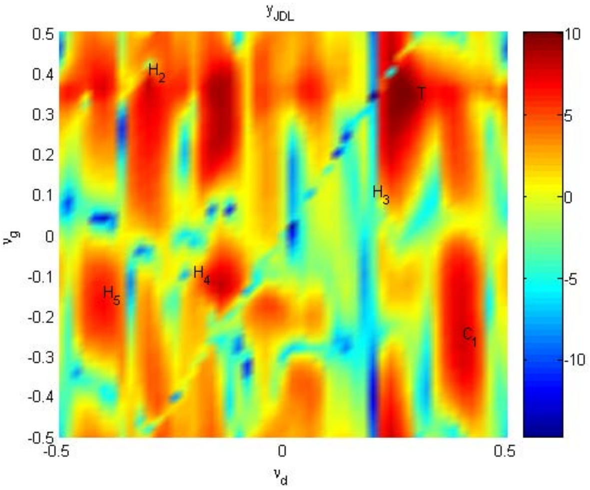

Figure 4: Output of the adaptive filter (JDL method)

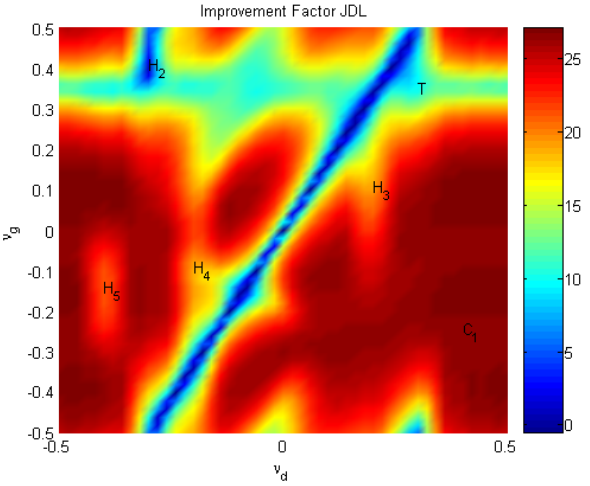

Figure 5: Improvement Factor (JDL method)

Figures 2 to 5 show how efficient PC and JDL method can be. This efficiency can even be improved by excising nonhomogeneities from training data. This is shown on figure 5 where the difference between each peak and the average level is increased when applying nonhomogeneities suppression (green curve).

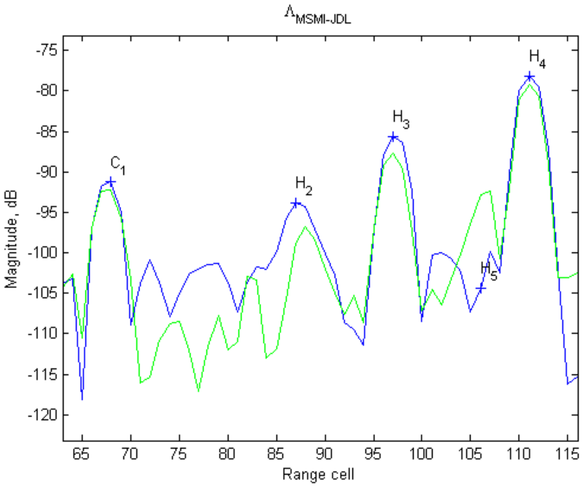

Figure 6: Improvement of detectability using nonhomogeneities selection.

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