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► **To cite this version:**

Alessandro Benfenati, Emilie Chouzenoux, Jean-Christophe Pesquet. A Proximal Approach for Solving Matrix Optimization Problems Involving a Bregman Divergence. BASP 2017 - International Biomedical and Astronomical Signal Processing Frontiers workshop, Jan 2017, villars-sur-oulon, Switzerland. hal-01613292

HAL Id: hal-01613292

<https://hal.science/hal-01613292>

Submitted on 10 Oct 2017

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A Proximal Approach for Solving Matrix Optimization Problems Involving a Bregman Divergence

Alessandro Benfenati*, Emilie Chouzenoux*[†], and Jean-Christophe Pesquet[†],

* LIGM, University Paris-Est Marne-la-Vallée

[†] Center for Visual Computing, CentraleSupélec, University Paris-Saclay

Abstract—In recent years, there has been a growing interest in problems such as shape classification, gene expression inference, inverse covariance estimation. Problems of this kind have a common underlying mathematical model, which involves the minimization in a matrix space of a Bregman divergence function coupled with a linear term and a regularization term. We present an application of the Douglas-Rachford algorithm which allows to easily solve the optimization problem.

In recent years, some applications such as shape classification models [1], gene expression [2], or inverse covariance estimation [3] have led to matrix variational formulations of the form:

$$\underset{C \in \mathcal{S}_+}{\text{minimize}} \quad D_f(C, S) + g(C) \quad (1)$$

where \mathcal{S}_+ is the cone of symmetric semidefinite positive matrices of size $n \times n$, S is a given matrix in \mathcal{S}_+ , f and g are proper lower-semicontinuous (lsc) convex functions defined on the space of $n \times n$ matrices, and D_f is the Bregman divergence associated with f . Recall that

$$D_f(C, S) = f(C) - f(S) - \text{tr}(T(C - S)) \quad (2)$$

where $T \in \partial f(S) \neq \emptyset$. Note also that solving (1) amounts to computing the proximity operator of $g + \iota_{\mathcal{S}_+}$ at S ,¹ with respect to the divergence D_f , which has also been found to be useful in a number of recent works [4], [5].

Very often, due to the nature of the problems, the regularization functional g has to promote the sparsity of C . A generic class of regularization is obtained by assuming that $g = g_0 + g_1$ where

$$g_0(C) = \begin{cases} \psi(d) & \text{if } C \in \mathcal{S}_+ \\ +\infty & \text{otherwise,} \end{cases} \quad (3)$$

where $\psi: \mathbb{R}^n \rightarrow]-\infty, +\infty]$ is a proper lsc function and d is the vector of eigenvalues of C , whereas g_1 is a function which cannot be expressed under this form. Typical examples are the nuclear norm $\|\cdot\|_*$ (or any Schatten norm) for g_0 and the ℓ_1 norm $\|\cdot\|_1$ (of the matrix elements) for g_1 [6].

In this paper, we will assume that function f can be expressed similarly to g_0 as $f(C) = \varphi(d)$ if $C \in \mathcal{S}_+$, $f(C) = +\infty$ otherwise, where $\varphi: \mathbb{R}^n \rightarrow]-\infty, +\infty]$ is a proper lsc convex function. In particular, this assumption is satisfied when

$$f(C) = \begin{cases} -\log \det(C) & \text{if } C \succ 0 \\ +\infty & \text{otherwise.} \end{cases} \quad (4)$$

Various algorithm have been proposed to solve Problem (1) when f is the above function and some specific choices of the function g are made: the popular GLASSO algorithm [3], a Gradient Projection method [1], and a splitting technique on the regularization term [6]. Here we propose to employ the Douglas-Rachford algorithm [7], which enables us to solve (1) in a fast manner, as soon as an efficient procedure for the eigenvalue decomposition is provided. The

Douglas-Rachford approach alternates proximity steps on $D_f(\cdot, S) + g_0 + \iota_{\mathcal{S}_+}$ and on g_1 . For many functions g_1 of practical interest, the proximity operator of g_1 (e.g, $g_1 = \|\cdot\|_1$) has a closed form solution [7]. Let us define $F(C) = f(C) + g_0(C)$. Let $\gamma \in]0, +\infty[$. It can be noted that computing the proximity operator of $\gamma(D_f(\cdot, S) + g_0 + \iota_{\mathcal{S}_+})$ w.r.t. the Frobenius metric $\|\cdot\|_F$, at some symmetric matrix \bar{C} , is equivalent to find

$$\hat{C} = \underset{C \in \mathbb{R}^{n \times n}}{\text{argmin}} \left(F(C) - \text{tr}(TC) + \frac{1}{2\gamma} \|C - \bar{C}\|_F^2 \right).$$

Classical properties of the proximity operator [7] state that

$$\hat{C} = \text{prox}_{\gamma F - \gamma \text{tr}(T \cdot)}(\bar{C}) = \text{prox}_{\gamma F}(\bar{C} + \gamma T).$$

Moreover, if $\bar{C} + \gamma T = U \text{Diag}(\sigma) U^\top$ where U is an orthogonal matrix and $\sigma \in \mathbb{R}^n$, then $\hat{C} = U D U^\top$ with $D = \text{Diag}(\text{prox}_{\gamma(\varphi+\psi)}(\sigma))$. For example, if f is the log-det function (4) and $g_0 = \mu \|\cdot\|_*$ where $\mu \in [0, +\infty[$, according to [8], the diagonal matrix of eigenvalues of \hat{C} is given by

$$D = \frac{1}{2} \left(\Sigma - \gamma \mu I_n + \sqrt{(\Sigma - \gamma \mu I_n)^2 + 4\gamma I_n} \right)$$

where $\Sigma = \text{Diag}(\sigma)$. The operations to compute $\text{prox}_{\gamma(\varphi+\psi)}$ are thus component-wise.

The proposed Douglas-Rachford approach is easy to implement: if an efficient procedure for the eigenvalue decomposition is available, according to our numerical experiments, it is also very fast.

Acknowledgements: This work was supported by the Agence Nationale de la Recherche under grant ANR-14-CE27-0001 GRAPHISIP.

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¹ ι_E designates the indicator function of a set E .