# Impact of the Approximated On-Line Centering and Whitening in OL-JADE on the Quality of the Estimated Fetal ECG

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## Abstract

*OL-JADE is an on-line method for fetal ECG extraction from non-invasive potential recordings, able to work in real-time on a DSP. With respect to the original JADE algorithm, it exploits a recursive sample-by-sample approximated centering and whitening stage that partially violates the requirements of the subsequent JADE stage.*

*In this paper this aspect is investigated showing a comparison with another similar algorithm, tracking BLISS, on artificial mixtures of real signals. OL-JADE presents a reduced complexity and, in case of time variances in the mixing process, permutations are confined to the involved sources. The imperfect centering and whitening have limited consequences in terms of signal distortions in presence of time variances, restricted to the time span of such variations.*

## 1. Introduction

Independent Component Analysis (ICA) showed to achieve good performance in non-invasive fetal ECG (FECG) extraction [1]. When the superficial biopotentials are taken on the pregnant's abdomen, the FECG is mixed to other interfering sources, both physiological (mother's ECG, EMG, breath) or artificial. Under the hypothesis of linear instantaneous mixing, this problem can be modelled as $\mathbf{x} = \mathbf{A}\mathbf{s}$, where $\mathbf{x}$ and $\mathbf{s}$ are the multidimensional random variables representing the mixtures and the original sources respectively. An ICA approach tries to indirectly estimate the statistically independent sources $\mathbf{s}$ finding a separation matrix $\mathbf{B}$ so that $\hat{\mathbf{s}} = \mathbf{B}\mathbf{x}$. The separation is ensured only if some fundamental conditions behind the ICA model are respected [2] but both the order and the absolute power of the estimated sources remain undetermined.

Batch ICA methods compute off-line the linear transformation $\mathbf{B} = \mathbf{R} \cdot \mathbf{W}$ in 2 stages, respectively providing a whitening matrix $\mathbf{W}$ and the remaining rotation matrix $\mathbf{R}$ needed to identify the independent components. Whitening decorrelates the centered input data, using all the second order statistics (SOS) information and thus the following stage must resort to higher order statistics (HOS) to accomplish its task. When whitening is mandatory, as for some algorithms, it should be exact in order to leave to the HOS stage only an orthogonal matrix to identify [2].

OL-JADE is an on-line algorithm for FECG extraction able to operate in real-time on a floating-point DSP [3]. To achieve a separation quality closed to that achievable with the original batch JADE algorithm [4], adding the tracking capabilities, it implements a block-on-line approach with several strategies, among which an approximated sample-by-sample centering and SOS stage. Due to the continuous update of the whitening matrix, it produces smooth variations of the whitened signals reducing permutations [5], responsible of a scrambling of the estimated sources between adjacent blocks. Such an imperfect whitening potentially violates the requirements of JADE.

In this paper we evaluate the influence of such approximations on the quality of the separation, comparing the performance of OL-JADE with another state-of-the art algorithm we found to be very similar in principle to OL-JADE but with the ability to perform exact whitening. Time-variant scenarios with synthetic mixtures of real signals allow to assess the performance and the tracking ability with respect to the implemented SOS stage.

## 2. Methods

OL-JADE [3] is a block-on-line technique derived from the ICA algorithm JADE. It is based on an approximated centering and whitening of the input frame followed by a sliding window update of the whitened signals on which, after a preconditioning of the process, the HOS stage of JADE can take place identifying a rotation matrix $\mathbf{R}_k$. $\mathbf{R}_{k-1}$ is exploited to perform a coarse separation of the current block, then refined by the HOS stage applying a series of small rotations leading to a final Givens matrix $\mathbf{G}_k$ such that $\mathbf{R}_k = \mathbf{G}_k \cdot \mathbf{R}_{k-1}$. Differently from JADE, which estimates $\mathbf{B} = \mathbf{R} \cdot \mathbf{W}$ in 2 stages on a block of data, the first stage of OL-JADE is carried out sample-by-sample, i.e. $\mathbf{z}(i) = \mathbf{W}(i) \cdot \mathbf{x}_c(i)$, where the whitening matrix is updated as in [6]:

$$\mathbf{W}(i+1) = \\ = \mathbf{W}(i) - \frac{\lambda_0}{1+\lambda_0 \mathbf{z}^T(i)\mathbf{z}(i)}(\mathbf{z}(i)\mathbf{z}^T(i) - \mathbf{I})\mathbf{W}(i) \quad (1)$$

and $\mathbf{x}_c(i) = \mathbf{x}(i) - \overline{\mathbf{x}}(i)$ with

$$\overline{\mathbf{x}}(i) = (1-\gamma)\overline{\mathbf{x}}(i-1) + \gamma\mathbf{x}(i), \quad (2)$$

where $\gamma$ is a forgetting factor [3]. This recursive centering avoids abrupt changes between adjacent blocks of data and, even if approximated, it is quite accurate in this application. However, the absence of a single whitening matrix $\mathbf{W}$ for a block of data is in contrast with the original formulation of JADE. To estimate the effect of such an approximation we compared OL-JADE with other algorithms in literature, characterized by a block-on-line processing but with a block-by-block SOS stage. To this aim, it is possible to use the original JADE algorithm applied block-wise (BB-JADE [5]) and tracking BLISS (tBLISS) [7], customized with the same parameters of the sliding window used in OL-JADE and exploiting the HOS stage of JADE. Since BB-JADE requires a manual reordering of the extracted sources block-wise, but in every block produces a result very close to that achievable with tBLISS, for the sake of conciseness only the comparison with tBLISS will be presented hereafter.

tBLISS SOS stage finds the whitening matrix $\mathbf{W}$ block-wise as $\Lambda^{-1/2}\mathbf{U}^T$, where $\Lambda$ is the eigenvalues matrix of the correlation one for the current block of centered mixtures, and $\mathbf{U}$ is the orthogonal matrix of the corresponding eigenvectors. $\mathbf{U}$ is found by the Jacobi method iteratively applied in order to diagonalize the correlation matrix. To avoid permutations in the SOS stage, tBLISS exploits a sliding window approach followed by a preconditioning of the rotation for $\mathbf{U}$ so that $\mathbf{U}_k = \mathbf{U}_{k-1}\mathbf{U}$, with $\mathbf{U}_{k-1}$ and $\mathbf{U}$ respectively computed with the Jacobi algorithm for the previous block and for the current (preconditioned) one. This approach is similar to the one, described above, used in OL-JADE at the HOS stage.

To evaluate the impact of the different SOS stage, we used synthetic mixtures of real signals. Being known the sources, it is possible to exploit the *rms* error to quantify the separation quality. The sources come from the Physiobank MIT-BIH Polysomnographic Database [8, 9], and consist of 4 signals (Fig. 1) 50 seconds long, sampled at 250Hz. Three of these come from a single subject (signal *slp32*) and they have been used to represent the maternal sources: ECG (MECG), breath and EMG. The fourth signal (*slp48*) has been artificially downsampled by 2 and then played back at 250Hz to represent an FECG.

## 3. Results

Previous works [3, 5] demonstrated that in presence of time-invariance in the mixing process, OL-JADE results are very close to those achievable with the batch JADE algorithm. To emulate a time-variant mixing process, the original sources are multiplied for a random mixing matrix $\mathbf{A}$ whose rotational component has been constructed so that the elementary Givens matrix responsible for the couple of sources $(EMG, breath)$, and then the associated angle, is varied using different trends, whereas the others remain constant. Two interesting cases are reported here where, with respect to the initial configuration of $\mathbf{A}$, the aforementioned angle is:

- changed at 26th block of 20 degrees (*step trial*);
- linearly changed of 20 degrees in the interval between the 19th and 32nd block (*ramp trial*).

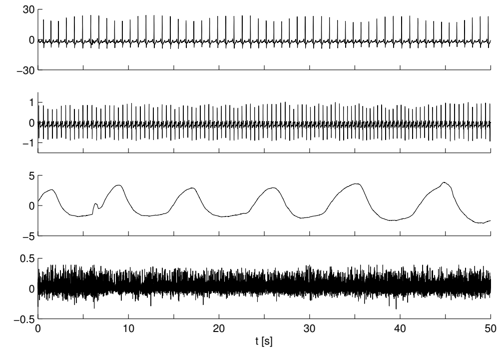


Figure 1. Sources used to create the artificial mixtures.

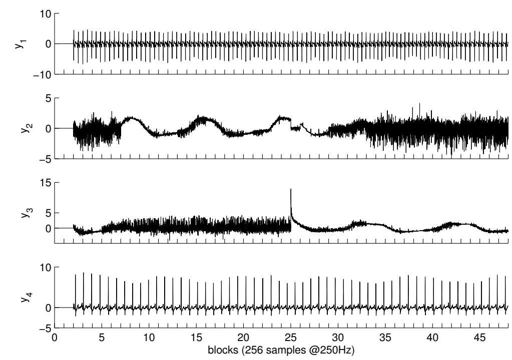


Figure 2. *Step trial*: OL-JADE estimated sources.

Fig. 2 and Fig. 3 respectively show the independent sources estimated by OL-JADE and tBLISS, for the *step* trial. The two algorithms demonstrate tracking ability in presence of time variances in the mixing process, but both of them show a permutation along with a strong distortion of the EMG and breath sources in the proximity of the transition region. The *rms* diagram on Fig. 4, showing the *rms* error of the estimated sources (properly reordered, normalized and centered) for both the algorithms, demonstrates that just the noise sources are affected by an increased es-

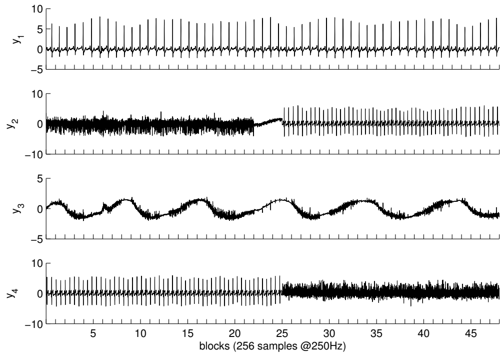


Figure 3. *Step trial*: tBLISS estimated sources.

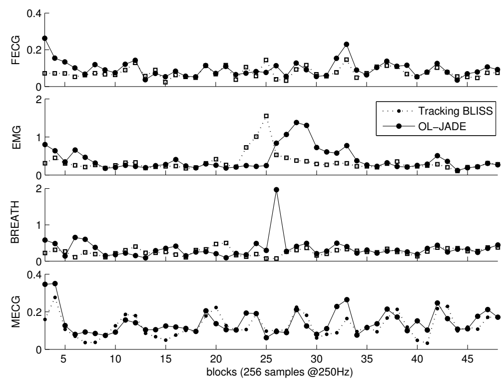


Figure 4. Comparison of the rms error for OL-JADE and tBLISS in the *step trial*.

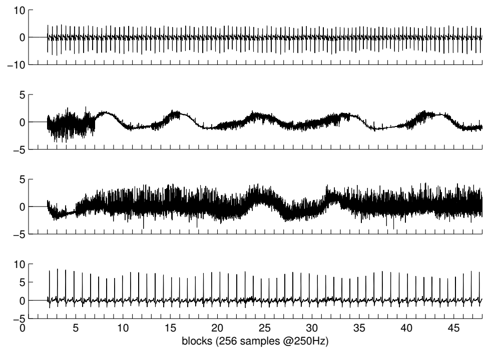


Figure 5. *Ramp trial*: OL-JADE estimated sources.

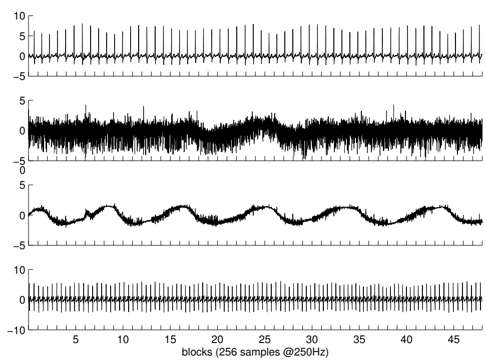


Figure 6. *Ramp trial*: tBLISS estimated sources.

timation error. This error has about the same entity for both the algorithms but for OL-JADE it is spread along a wider window preceding (due to the algorithm formulation [5]) and following the mixing change. This is also due to the SOS gradient-based stage, slowly converging to a new estimate of the whitening matrix for the input data. Nevertheless, both the algorithms produce FECG traces with an adequate quality, with the important advantage for OL-JADE that the FECG and the MECG, not involved in the time variance, don't experience permutations.

The *ramp* trial presents a more likely situation: the gradual variation of the mixing process is tracked by OL-JADE and tBLISS as expected, so that permutations are avoided in the estimated sources, as shown in Fig. 5 and Fig. 6 respectively. Nevertheless in this case, during the transition, it is possible to observe an unsuccessful separation between the noise sources, which lasts about for the same time for both the algorithms. This is due to the fact that in this case it is not possible to find a unique time-invariant mixing process that can be inverted. This can be easily demonstrated looking at the effect of the application of the original batch JADE algorithm over the signals in the *ramp* trial in Fig. 7, where it is possible to see an "average response" for the whole duration of the signal, i.e. a bad separation throughout the signal.

A more complete analysis can be carried out exploiting the *rms* error plot in Fig. 8. In this case OL-JADE sources were free from the distortions introduced by the step variation of the previous case that the HOS stage inherits from the SOS one without the possibility to perform any correction. At the same time it is possible to note that for both methods there is an increase in the *rms* error even for the FECG and MECG, which is higher for OL-JADE. This is caused by the combination of the approximated SOS and the limited window size for the HOS stage. Both lead to a poor estimate of the noise sources which has an impact on the identification of the other sources. In this case this effect is negligible but it could be worth to avoid trusting the estimated sources during transitions of the mixing process, as already said.

## 4. Discussion and conclusions

From the results presented in Sect. 3, it is possible to conclude that the approximations introduced in OL-JADE

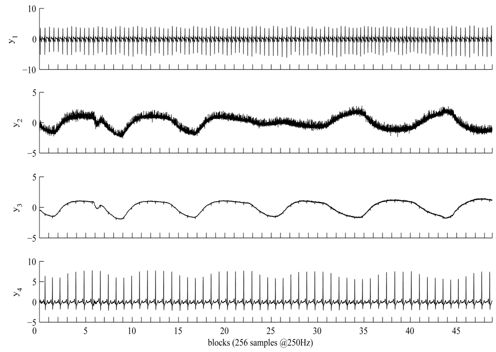


Figure 7. *Ramp trial*: batch JADE estimated sources.

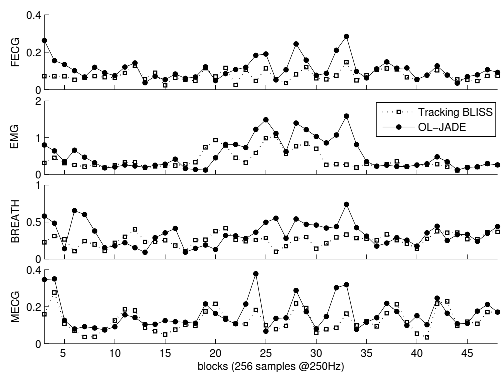


Figure 8. Comparison of the rms error for OL-JADE and tBLISS in the *ramp trial*.

have a limited effect on the achievement of a good separation in absence of time variances in the mixing process but also in case of time variances not involving the FECG sources, even if some distortions could appear in the estimated sources. However, in the time-variant case, due to the block-by-block application of the HOS stage, the blocks interested by such dynamic changes cannot be correctly processed, regardless the correctness of the adopted whitening process. With respect to tBLISS, a method providing an exact whitening, sources distortion in proximity of the changes in the mixing process lasts for a longer time on the interested sources with OL-JADE, producing a small increase in the estimation error even for the other sources, but it can be imputed to the whole algorithm structure, not only to the SOS stage. The algorithms have been tested adopting the same approximated centering of OL-JADE, which introduces only negligible second-order effects in the context of this application.

Even though a precise SOS as the one provided by tBLISS is preferable from a theoretical viewpoint, it should be noted that it comes at the expenses of an increased computational complexity to be considered for real-time implementations. Furthermore, in that case, a permutation avoidance mechanism of OL-JADE, residing in the sample-by-sample nature of the SOS process, is lost and then it is possible to have permutations even between sources not interested by the time variance.

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