# Robust and mask free phase unwrapping technique dedicated to $B_0$ and $T_2^*$ phase imaging

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## Introduction

The phase unwrapping problem occurs in different engineering domains, such as Synthetic Aperture Radar (SAR) or MR imaging. Concerning MR, phase unwrapping can be applied directly into clinical practice (e.g. in MR angiography), but also, it can be used to estimate and adjust various MR acquisition related parameters, or to correct for some image acquisition artifacts. The latter comprises $B_0$ mapping, commonly used to tune the shim coil currents thus improving the static field uniformity, and evaluation of geometric distortions due to susceptibility effects related to fast acquisition techniques, such as echo-planar or echo-volumar schemes [1][2]. While the true unwrapped phase is of the form $\theta_{i,j}=\phi_{i,j}+2k\pi$ T at position (i,j) of the phase image ($\phi_{i,j}\in]-\pi,\pi]$ , k is an integer), we are able to measure only the base $\phi_{i,j}$ phase. The estimates of the unwrapped phase must result in a spatially smooth phase map, without any $2\pi$ jump.

## Material and Methods

Existing unwrapping techniques can be divided into two classes: the path-following methods and the minimum-norm methods [3]. The first class uses either identification of the residues, or region-growing technique, following the best path to unwrap the data. The second class relies on a generalized minimum $L^p$ norm reformulation of the problem. In this case, the local derivatives of the unwrapped phase should match the derivatives of the measured (wrapped) phase, as closely as possible. Contrary to a relatively uniform content of SAR objects, MR images objects are less homogeneous, and can consist of tissue, bone or air. The phase information obtained from regions containing bone or air lacks coherence and is characteristic of noise. In order to remove the contribution of such regions, a mask is generally defined containing only those voxels that will be consequently used for phase unwrapping. The estimated phase map quality depends heavily on how accurate we can delineate the mask. A commonly employed thresholding of the magnitude image is generally insufficient because it does not insure that only brain tissue is selected. For instance, the areas corresponding to muscle in primate can be larger than those corresponding to the brain, yielding unwanted new residues. The solution to this problem is to use a correlation map **c** that automatically weighs the contribution of each image object component. In this study, we proceed in two steps: first, we use a 2D weighted full multigrid algorithm to unwrap the phase map in the acquisition plane involving a minimum $L^2$ norm method; second, we employ a deterministic weighted-least square unwrapping technique in order to unwrap slices along the third direction using the same correlation map **c** for the weighting. One of the reasons that we opted for minimum-norm methods was the computation speed.

The minimum $L^2$ norm solution is obtained by minimizing the weighted least square error:

$$\varepsilon^2 = \sum_{i,j} C^x_{i,j}\left(\theta_{i+1,j}-\theta_{i,j}-\Delta^x_{i,j}\right)^2 + \sum_{i,j} C^y_{i,j}\left(\theta_{i,j+1}-\theta_{i,j}-\Delta^y_{i,j}\right)^2 \text{ with } C^x_{i,j}=\min\left(c^2_{i+1,j},c^2_{i,j}\right) \text{ and } C^y_{i,j}=\min\left(c^2_{i,j+1},c^2_{i,j}\right)$$

and the wrapped phase gradients $\Delta^x_{i,j}=\omega\left(\phi_{i+1,j}-\phi_{i,j}\right)$ and $\Delta^y_{i,j}=\omega\left(\phi_{i,j+1}-\phi_{i,j}\right)$ ($\omega$ is the wrapping operator that wraps the phase onto the $]-\pi;\pi]$ interval). The solution is obtained using a Gauss-Seidel relaxation method by iterating the following scheme initialized to null solution:

$$\theta_{i,j}=\frac{C^x_{i,j}\theta_{i+1,j}+C^x_{i-1,j}\theta_{i-1,j}+C^y_{i,j}\theta_{i,j+1}+C^y_{i,j-1}\theta_{i,j-1}-L_{i,j}}{C^x_{i,j}+C^x_{i-1,j}+C^y_{i,j}+C^y_{i,j-1}} \text{ with the phase Laplacian } L_{i,j}=C^x_{i,j}\Delta^x_{i,j}-C^x_{i-1,j}\Delta^x_{i-1,j}+C^y_{i,j}\Delta^y_{i,j}-C^y_{i,j-1}\Delta^y_{i,j-1}\,.$$

Typically, this relaxation converges too slowly and needs to be accelerated by using a pyramidal multigrid method, that employs: 1) a non-linear restriction operator that enables moving from a fine N×N grid to a coarser N/2×N/2 grid, 2) the Gauss-Seidel relaxation previously described, 3) a prolongation operator that adapts the intermediate coarse solution back to the higher resolution grid. The convergence is therefore speed up by quickly finding a coarse approximation of the solution and performing cycles known as V-cycles (for fine-coarse-fine scales) to reach the optimal solution.

## Results and Discussions

Gradient echo data were acquired on a macaque using a 2D FLASH pulse sequence on a Siemens 7T Human Investigational Device (Siemens, Erlangen) endowed with a 7cm loop antenna and setting the following parameters : flip angle FA=25°, $T_E$=25ms, $T_R$=500ms, 4 averages, asymmetric FOV=12.4×10.1cm², matrix 832×1024, BW=30Hz/pixel. The monkey was anesthetized and monitored during the procedure.

The unwrapping technique was applied on the signal phase of the MRI signal without using any mask of the money brain. Figure 1a depicts the phase image before unwrapping and highlights numerous phase jumps that occur at high magnetic fields, depending on the quality of the shim. Figure 1b represents a quality map of pseudo-correlation processed from the wrapped phase itself. Homogeneous tissues are characterized by values close to 1 whereas values for bone or air regions remain close to 0. Figure 1c depicts the result of the unwrapping procedure, showing no phase jump inside the brain phase map. Figure 1d provides an inverse video zoom of the occipital lobe showing the improved contrast obtained between grey and white matter in comparison to the magnitude image, as well as new vascular information in the cortex and perpendicular to the cortical surface, as previously described in [4].

## Conclusion

We introduced a fast and robust technique for unwrapping phase that do not necessitate employment of region masks. This technique seems to be quite efficient even at high fields, where $B_0$ inhomogeneities and susceptiblity artifacts may result in numerous phase jumps in raw phase images.

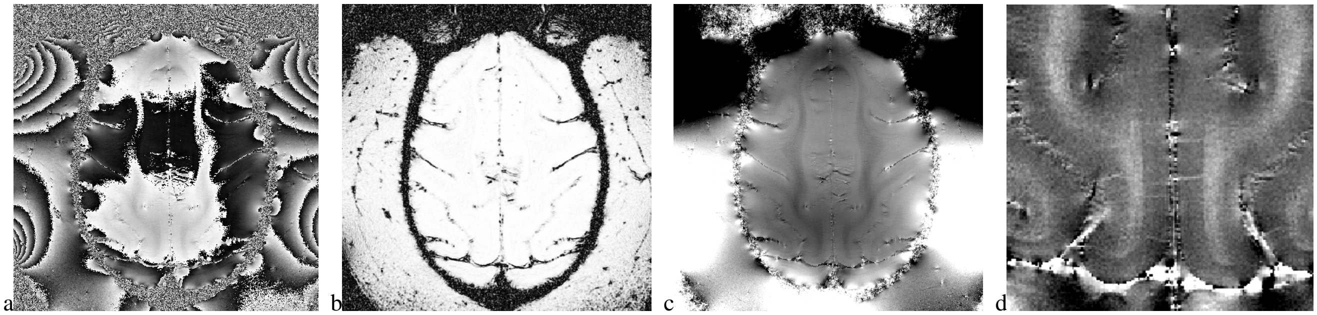

Figure 1 : Unwrapping of 2D GRE phase signal at 7T a) wrapped phase map ; b) quality map ; c) unwrapped phase map ; d) inverse video zoom of the occipital lobe

## References

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