Quality-based UnwRap of SUbdivided Large Arrays (URSULA) at 9.4T

Johannes Lindemeyer[1], Ana-Maria Oros-Peusquens[1], Kaveh Vahedipour[1], and N. Jon Shah[1,2]

[1]*Institute of Neuroscience and Medicine 4, Forschungszentrum Jülich, Jülich, Germany,* [2]*Department of Neurology, Faculty of Medicine, JARA, RWTH Aachen University, Aachen, Germany*

Target Audience: Scientists concerned with MR phase imaging, B_0 field mapping, quantitative susceptibility imaging (QSM) and related topics.

Purpose: As phase and susceptibility contrast have gained importance in the last decade, phase unwrapping has been approached in many ways. Spatial characteristica as well as the evolution of phase in time (for multi echo datasets) can be used for a successful unwrap (e.g. [1-4]). High-resolution imaging is used routinely in ultra-high field MRI (7T and above) resulting in the acquisition of large data arrays. This dramatically increases the demands on the computing time for unwrapping algorithms. In this abstract a new method, (P-)URSULA, is presented, making use of an artificial volume compartmentalisation and a computing paralellisation to optimise the unwrapping process. The presented algorithms are based on quality-guided phase unwrapping, such as described in [5].

Theory: Volumetric phase data as observed in MRI correspond to distributions of magnetic field variations and chemical shifts. The relation between phase, the static magnetic field and the chemical shifts can be approximated by: $\varphi(\vec{x}, t) \approx \mathrm{mod}_{2\pi}(\gamma \cdot \Delta B(\vec{x}) \cdot t)$ (neglecting a spatially inhomogeneous initial phase). Unwrapping intends to reconstruct the unmodulated term inside the brackets. This is in principle feasible as long as the function fulfills the Nyquist theorem almost everywhere regarding the voxel spacing and the interval between time points. Abdul-Rahman et al. [5] described a way to spatially unwrap phase data by assigning edge qualities to voxels and the surfaces in-between. Quality-based unwrapping (QBU) unwraps and groups voxels progressively with descending edge quality. This produces very stable unwrap results, but implies a huge computing time for a large data array size. The concept behind the present algorithm is to subdivide the imaged volume into a number of subsets. Here we choose volumes produced by a regular grid. For each subset, an individual unwrap applying QBU is performed. The individual phase images might be mismatched by a constant offsets of $n \cdot 2\pi$ (n = ±1,2,3,...). Although the phase is computed sequentially for each of the volume subsets, the reduced number of conditions and quicker seek-and-assign operations per subset lead to a significant gain in computational speed. In order to produce the full-volume, phase image from the unwrapped phase subsets all subsets must be offset-matched. A quality-based, edge-matching algorithm was developed to achieve this. For each subset a so-called *connectivity* (percentage of the subset edges shared with neighbouring subsets and the mask support) is estimated and a progressive $n \cdot 2\pi$ matching process is performed. Fig. 2 demonstrates the workflow of the URSULA algorithm. Fig. 1 illustrates the rating of subset connectivities before offset-matching is performed.

Furthermore, an even more dramatic increase in computing speed can be achieved by distributing the unwrapping processes of the invdividual subsets to nodes on a cluster. Since each subset volume is unwrapped separately, the method is ideal for parallel computing. We call this technique P-URSULA (paralellised URSULA).

Materials: A healthy volunteer was measured on a Siemens 9.4T human scanner (Siemens Healthcare, Erlangen, Germany) after obtaining informed consent. A 3D multiple-echo gradient-echo sequence with TR=38ms was used. The resolution was 0.5mm isotropic and the matrix size was 308x448x80 (slab selective excitation was employed). The phase volume to be unwrapped was produced by combining the complex data corresponding to TE_1=3.93ms and TE_2=26.93ms (ΔTE=23ms). The (P-)URSULA framework including the QBU algorithm as well as the offset-matching algorithm were implemented in Matlab® (The MathWorks Inc.) with no further optimisation. The brain mask was designed by region growing using ITKSnap [6]. To facilitate a comparison of computing time, a synthetic dataset of size 128x128x128 was used; the synthetic data depicts the phase of a smoothed random complex field. QBU and URSULA were tested on a common 64bit workstation computer with 2x2.4GHz CPUs and 8GB of RAM, while P-URSULA was run on a local cluster (constituting of 40 nodes, 2.0-2.4GHz QuadCore Opteron). URSULA and P-URSULA used a subset-size of 40x40x40 voxel, with a grid of 64 individual subsets.
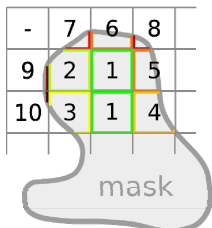

Fig. 1: Quality-based subset offset-matching (best rating: 1)

Results: The phase volume of the 9.4T in vivo measurement was successfully unwrapped within the mask confinement (see Fig. 2). For the synthetic data, the computing time for URSULA was 27min30sec, an order of magnitude faster than the whole volume QBU with 11h30min. We mention that occasionally URSULA can cause artefacts in the unwrapped map, when unexpected fringelines end on or close to a subset boundary. However, this is a rare occurence which can be avoided by slight changes in the subset size, thus shifting the borders. Despite this minor shortcoming, the algorithm is much more stable than slice-based unwrapping which completely ignores the relations in the 3rd dimension. P-URSULA significantly outperforms URSULA, taking only about 5min12sec on the computer cluster described above. It leads to the same result as URSULA.

Discussion/Conclusions: In terms of unwrap quality, URSULA offers a viable alternative to the traditional whole brain QBU while significantly reducing computing time. On the moderately-sized synthetic data used here, computation with URSULA was accelerated by approximately a factor of 25 compared to whole volume QBU. Phase discontinuities can appear near subset boundaries or noisy regions and must be taken care of, for example, by changing the number of subsets. Using P-URSULA, 3D unwrapping of huge arrays (e.g. order of 10^7-10^8 voxels) becomes feasible within minutes. The gain in computing speed is only limited by the number of cluster nodes available and the time demand for a single subset unwrap, but the reliability of the global unwrap tends to decrease with the size of generated subsets.

References:
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Wrapped Phase

(Parallel Computing)

unwrapping

Subset Offset Matching
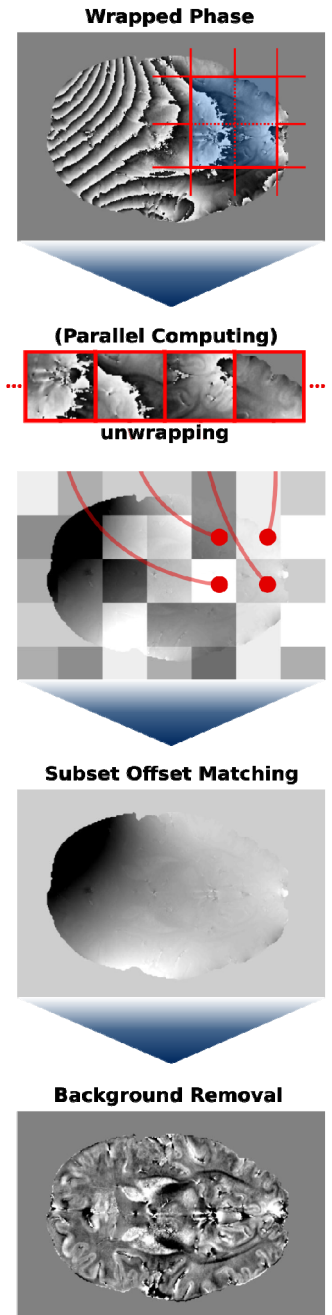

Background Removal

Fig. 2: URSULA workflow applied on 9.4T in vivo example; The bottom image shows an exemplary background correction of the unwrap result