Rapid Opensource Minimum Spanning TreE AlgOrithm for Phase Unwrapping (ROMEO)

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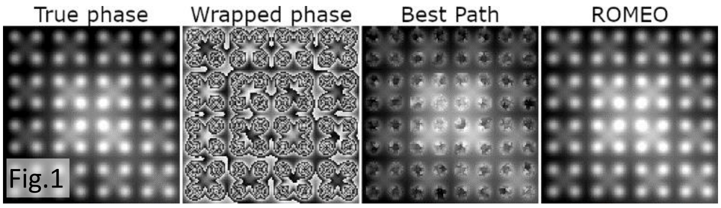
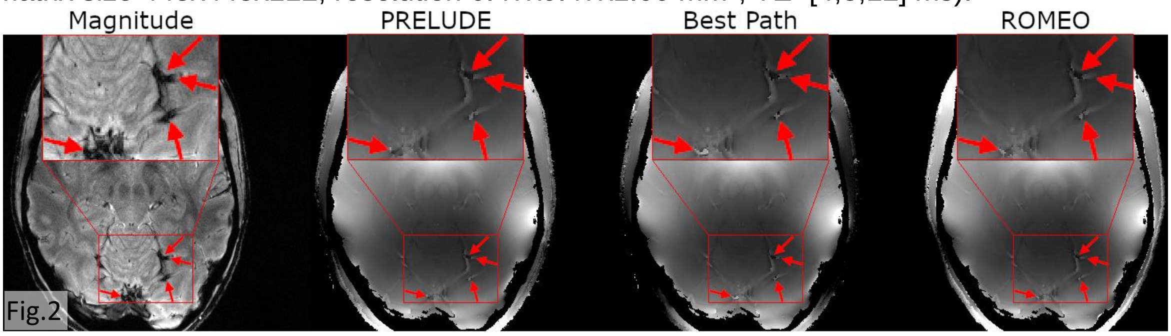
Introduction: Unprocessed MRI phase (θ) is wrapped into the 2π range causing abrupt changes in phase (wraps), which do not represent true spatial and temporal continuity of θ within the object. PRELUDE[1] is a robust and widely used benchmark 3D region-growing algorithm. It identifies and removes wraps but can take several hours/days to complete. An alternative, quality-guided algorithm, Best Path[2], unwraps voxels in decreasing order of the spatial phase coherence between voxels, which is faster but more prone to errors. We propose a new phase unwrapping algorithm, ROMEO, which uses phase as well as magnitude weights and allows single-step unwrapping of multi-echo data making it faster than PRELUDE or Best Path, but as accurate as PRELUDE.



Methods: ROMEO calculates up to 4 weights, which are multiplied to create the final quality map, finds the seed voxel with the highest weight and unwraps voxels in decreasing order of the weights according to a minimum spanning tree algorithm. The weights are: **1.** Spatial phase coherence weight – always applied: $W_i^{\theta,Spat} = 1 - \left|\gamma(\theta_i - \theta_j)/\pi\right|$, where γ-is a wrapping operator and *i,j* are two adjacent spatial locations. **2.** Temporal phase coherence weight – applied for multi-echo data: $W_{i,n}^{\theta,Temp} = \max\left(0,1 - \left|\gamma\left(\theta_{i,n} - \theta_{j,n}\right) - \gamma\left(\theta_{i,m} - \theta_{j,m}\right) \cdot TE_n/TE_m\right|\right)$, where *n,m* are two subsequent echoes. Weights 3. and 4. are applied if the magnitude data are available. **3.** Magnitude coherence weight: $W_i^{M1} = \left(\min\left(M_i, M_j\right) / \max\left(M_i, M_j\right)\right)^2$. **4.** Magnitude scaling weight: $W_i^{M2} = 0.5 + 0.5 \cdot \min\left(1, \min\left(M_i, M_j\right) / \left(0.5 \cdot M_{max}\right)\right)$, where M_{max} is the global maximum magnitude. ROMEO was compared to PRELUDE and Best Path on simulated magnitude and phase data with complex topography[3,4] (matrix size 256x256x256, TE=[4,8,10] ms) as well as *in-vivo* 7T 3D GRE data (matrix size 448x448x112, resolution 0.47x0.47x1.00 mm^3, TE=[4,8,12] ms).



Results: Fig.1 compares unwrapping by Best Path and ROMEO with all 4 weights for simulated data (TE=10 ms). Phase unwrapping errors are visible only for Best Path, which took ~38 s and used max 2.9 GB RAM. ROMEO took ~20 s and 1.7 GB and PRELUDE failed to deliver a result within 314 hours occupying 2.5 GB RAM per echo. At 7T, all three methods removed phase wraps throughout the brain except in a few voxels inside veins. Fig.2 shows examples of residual phase wraps inside the veins (arrows) that were largest with Best Path. PRELUDE took almost 30 hours to unwrap all 3 echoes and max 0.6 GB RAM for each echo, Best Path took ~27 s and 2.5 GB and ROMEO took ~25 s and 2.1 GB for all echoes. **Conclusions:** ROMEO is a new rapid and robust phase unwrapping technique that is faster than both PRELUDE and Best Path with similar accuracy to PRELUDE. ROMEO will be useful for phase imaging and QSM in challenging cases: at high fields or long echoes, especially close to air spaces or implants.

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