Distortion-free, multi-shot EPI with Blip-Up and Down Acquisition (BUDA) and structured low-rank reconstruction

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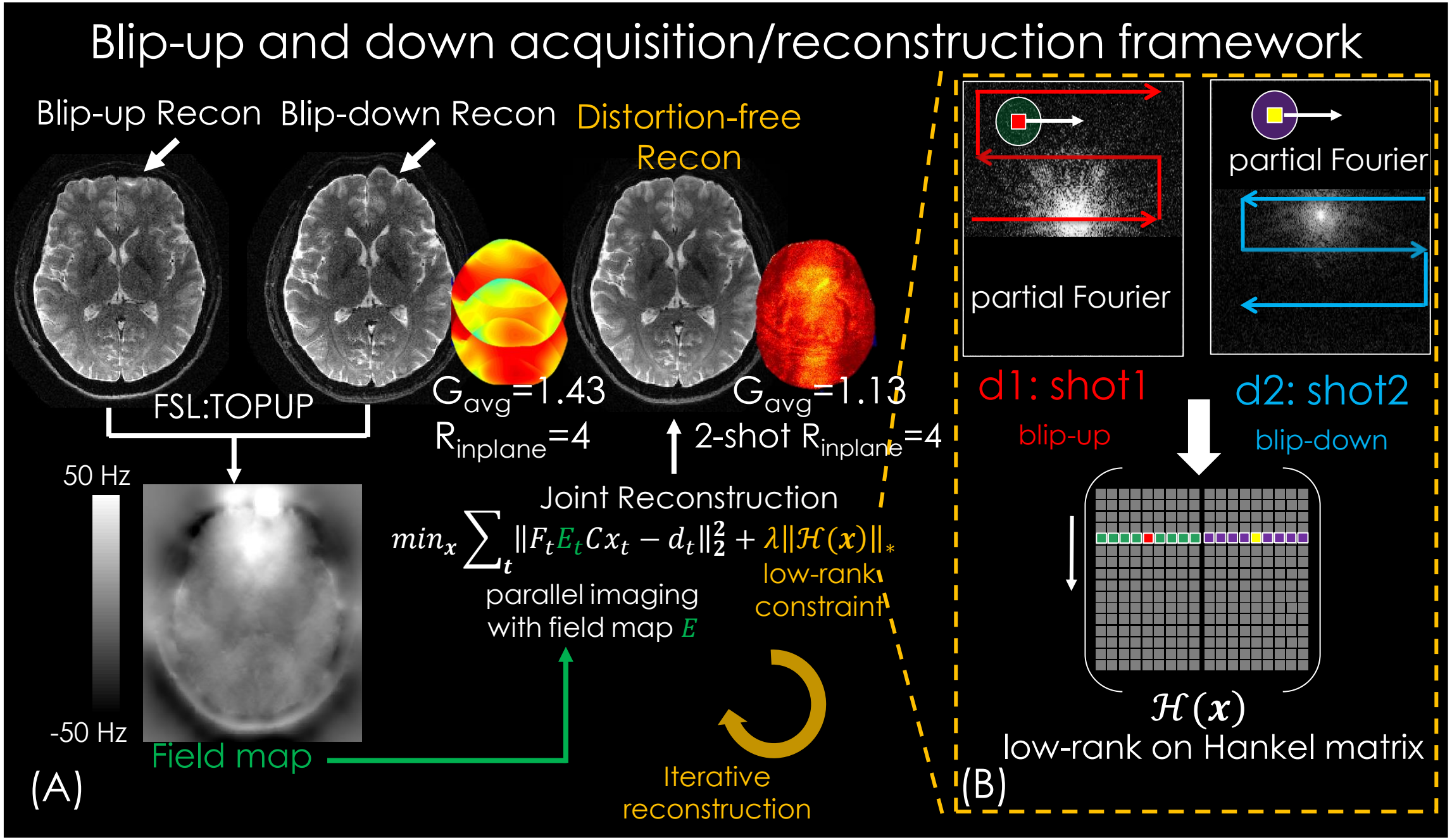
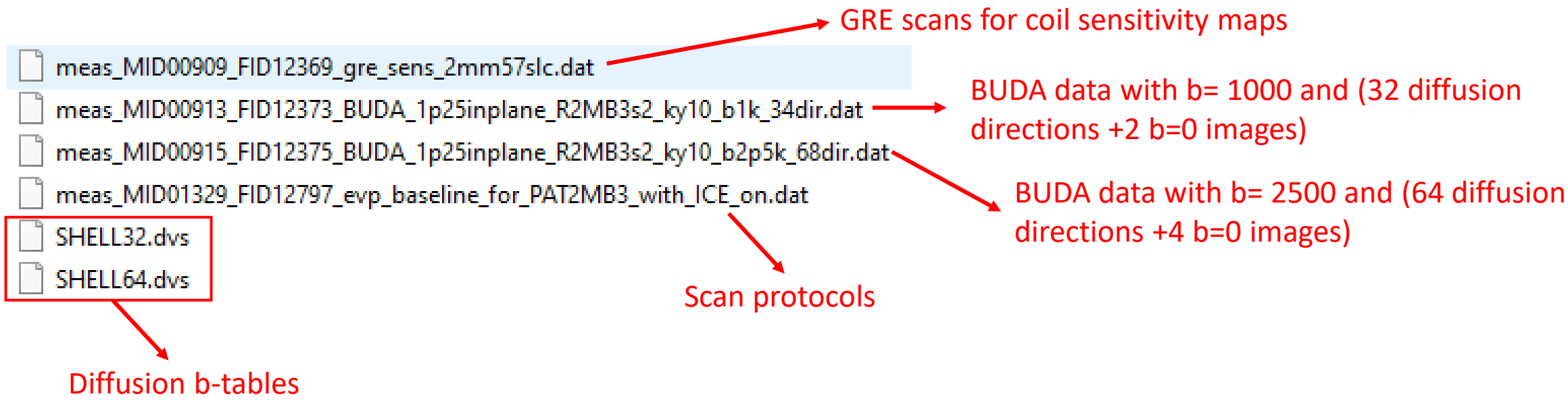

Blip-up and down acquisition/reconstruction framework
Blip-up Recon
Blip-down Recon
Distortion-free Recon
FSL:TOPUP
50 Hz
-50 Hz
Field map
G_{avg}=1.43
$R_{inplane}$=4
G_{avg}=1.13
2-shot $R_{inplane}$=4
Joint Reconstruction
$min_x \sum_t \|F_t E_t C x_t - d_t\|_2^2 + \lambda \|\mathcal{H}(x)\|_*$
parallel imaging with field map E
low-rank constraint
Iterative reconstruction
(A)
partial Fourier
partial Fourier
d1: shot1
blip-up
d2: shot2
blip-down
$\mathcal{H}(x)$
low-rank on Hankel matrix
(B)

Acquired in-vivo datasets



Download these datasets from :
https://drive.google.com/file/d/1DAeTW2iLgQx8tjZT3QqZ7F3vvt6Vwt2Q/view?usp=sharing

And then copy these datasets to ./data/ folder

The scan protocol of BUDA data

- FOV: 220 mm *220mm, matrix size: 176*176
- In-plane resolution: 1.25 mm *1.25mm
- Slice thickness: 2mm
- Number of slices: 57
- Number of coils: 32
- TR/TE = 2800/77 ms
- Effective echo-spacing = 0.37 ms
- Multi-band factor: 3 with CAPI-shift FOV/2 per shot
- In-plane acceleration factor :2 per shot
- partial Fourier factor: 0.75
- BUDA acquisition with AP shot kyshift 1 and PA shot kyshift 0
- Two shells: b= 1000 with 32 diffusion directions and b=2500 with 64 diffusion directions

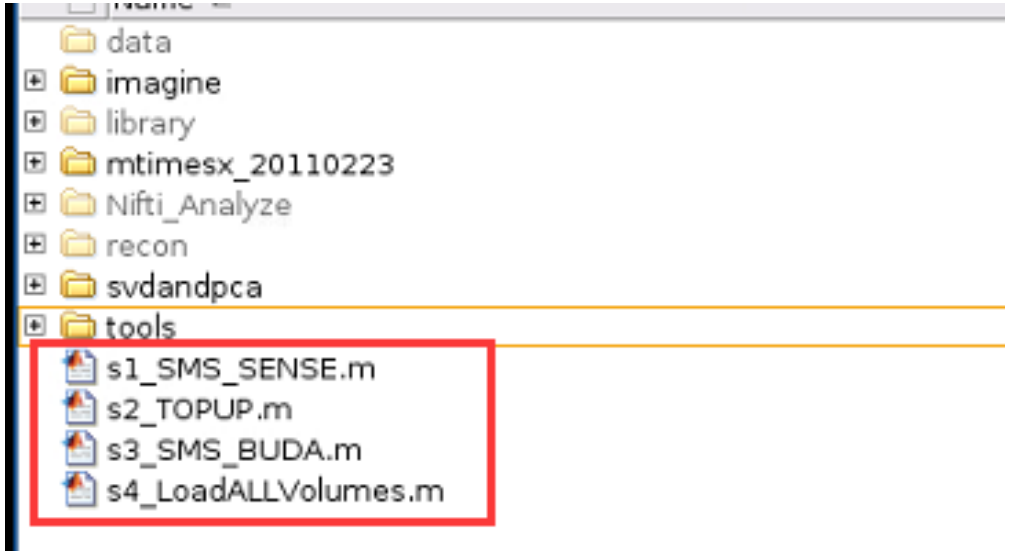
MATLAB offline reconstruction

- The reconstruction scripts have been tested on MATLAB 2015b.
- The reconstruction scripts have been tested on Linux OS.
- The scripts require BART toolbox and FSL software
  - BART toolbox 0.5.00 is recommended (https://zenodo.org/record/3376744)
  - FSL 6.0.4 is recommended (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FslInstallation)

  - **Warning: your workstation should have more than 64GB RAM and 50 GB storage to reconstruct the raw data!**

Reconstruction scripts

- Step1: run S1_SMS_SENSE.m to reconstruct each shot separately
- Step2: run S2_TOPUP.m to estimate the field maps between AP/PA shots
- Step3: run S3_SMS_BUDA.m to jointly reconstruct distortion-free BUDA-EPI
- Step4: run S4_LoadALLVolumes.m to load all volumes and combines AP/PA shots after removing background phase of each shot



S1_SMS_SENSE.m

- 1. file_name

```
28    %data path
29 -  file_path = './data/';
30 -  file_name = 'meas_MID00913_FID12373_BUDA_1p25inplane_R2MB3s2_ky10_b1k_34dir.dat';  % raw data of BUDA-EPI
31 -  evp_name = 'meas_MID01329_FID12797_evp_baseline_for_PAT2MB3_with_ICE_on.dat';  % scan protocols
32 -  gre_name = 'meas_MID00909_FID12369_gre_sens_2mm57slc.dat';  % gre scan for sensitivity map
33
```

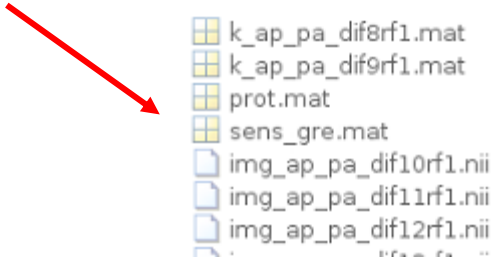
- 2. The “CoilSense_ESPIRIT3d” function is using BART toolbox. Make sure you installed BART successfully.

```
72    %% load GRE data and calculate sensitivity maps
73 -  if (~exist (strcat(save_path,'sens_gre.mat'),'file'))
74 -      fGRE=[file_path, gre_name];
75 -      [Img_gre, whmcc]= load_GRE_data_prewht(fGRE,N,Ncc);  % load ref data, do coil compression and noise prewhitening
76        % estimate ESPIRiT coil sensitivity
77 -      sens_gre = sq(CoilSense_ESPIRIT3d( permute(Img_gre, [1,2,4,3]))); % calculate coil sensitivity using ESPIRIT
78
```

- 3. Open this function, make sure the environment setting and folder path are correct

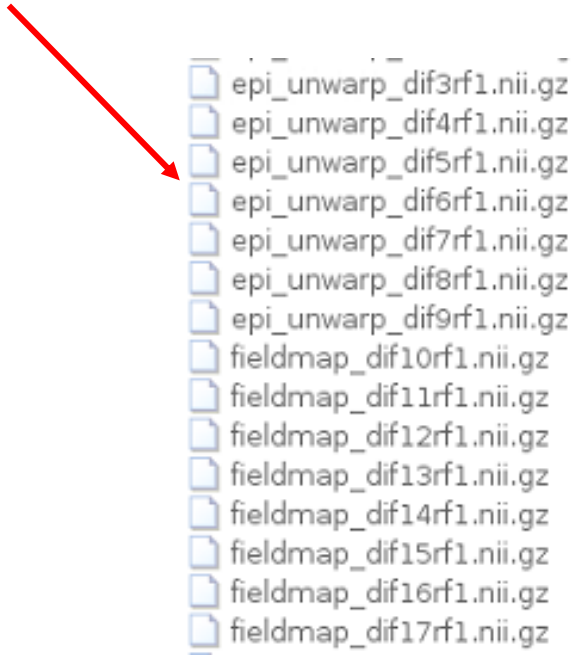
```
1   function sens = CoilSense_ESPIRIT3d(img_3d)
2   % this function is for 3d data, and estimates sensitivities in 3d
3
4
5   % img_3d: x,y,slice,chan
6   % data_path : path you want to write data
7   % sens : final coil sens output including all slices
8
9   ImSize = size(img_3d);
10  % code only work if matrix is even in size so mod matrix if it is odd
11
12  if rem(ImSize(1),2) == 1
13      img_3d = cat(1,img_3d,zeros(1,ImSize(2),ImSize(3),ImSize(4)));
14  end
15
16  if rem(ImSize(2),2) == 1
17      ImSizeCurrent = size(img_3d);
18      img_3d = cat(2,img_3d,zeros(ImSizeCurrent(1),1,ImSizeCurrent(3),ImSizeCurrent(4)));
19  end
20
21  if rem(ImSize(3),2) == 1
22      ImSizeCurrent = size(img_3d);
23      img_3d = cat(3,img_3d,zeros(ImSizeCurrent(1),ImSizeCurrent(2),1,ImSizeCurrent(4)));
24  end
25
26
27  addpath('/usr/local/app/bart/bart-0.5.00/matlab')
28
29  setenv('TOOLBOX_PATH','/usr/local/app/bart/bart-0.5.00')
30
31  setenv('TEMP_PATH','/dev/shm/');
32
33
```

- 4. The script will create SMS-SENSE reconstructed AP/PA shots and ghost-corrected undersampled k-space data



S2_TOPUP.m

- Make sure the FSL functions can be called on MATLAB
- This script will generate field maps as well as unwrapped EPI shots



S3_SMS_BUDA.m

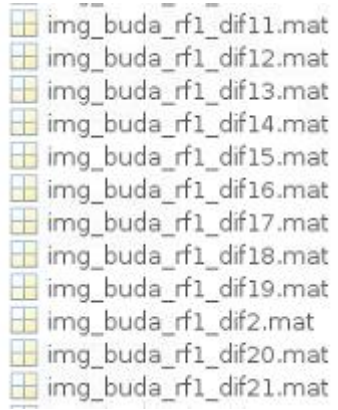
- BUDA settings:

```
38      % BUDA settings
39 -    opt.step_size = 0.8;
40 -    opt.num_iter = 150;    % 100 iterations
41 -    opt.tol = 0.25;
42 -    opt.winSize = [7,7]; % kernel size
43 -    opt.lambda_msl = 1.00;  % lambda of henkel low rank matrix
44 -    opt.esp=esp;    % echo-spacing
45 -    opt.PhaseShiftBase = pi;  % CAIPI shift of CAIPI
46 -    opt.show_mercy = show_mercy ;  % show how many cores you wanna use
47 -    opt.fista=1 ;  % --1 use FISTA algorithm  --0 use POCS algorithm
48 -    opt.t_k=1;
49
```

- You can also use non-parallel computing version to debug BUDA code

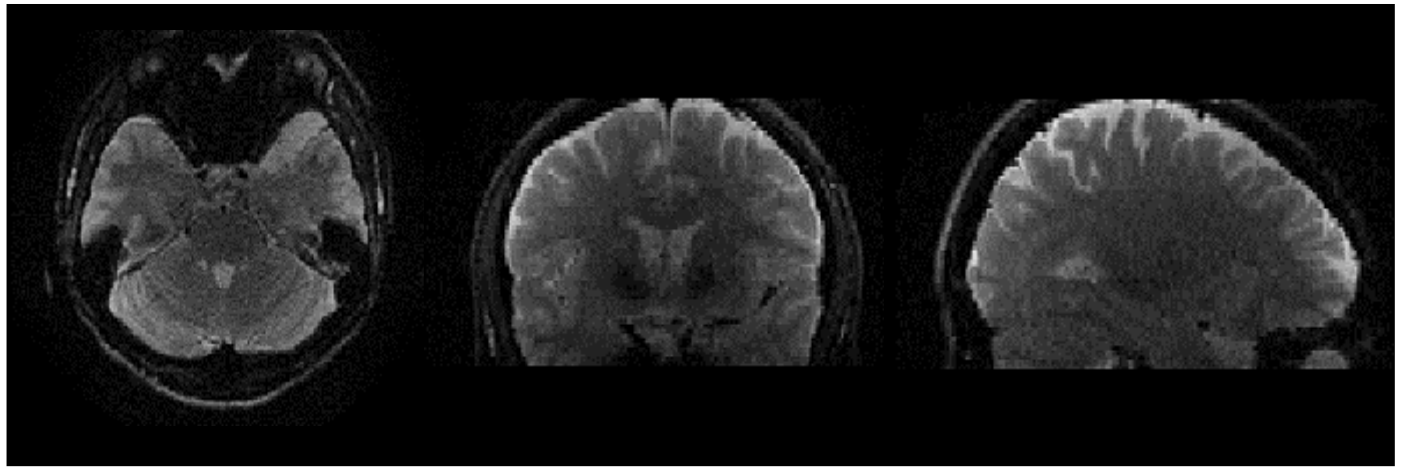
```
69 -        tic
70          % BUDA recon w/o parallel computing --it's slow, you can see the iterations
71  %       [img_msl]=recon_SMS_BUDA_XCLv2_fista (k_ap, k_pa,ky_idx_ap,ky_idx_pa,sens_gre, AccY, AccZ,img_fieldmap,opt);
72
73          % BUDA_recon with parallel computing
74 -        [img_msl]=recon_SMS_BUDA_XCLv2_parfor_fista (k_ap, k_pa,ky_idx_ap,ky_idx_pa,sens_gre, AccY, AccZ,img_fieldmap,opt);
75 -        toc
76
```

- This script will generate BUDA reconstructed images



S4_LoadALLVolumes.m

- load whole-brain volumes and do real-valued diffusion processing to combine BUDA shots
- This script will generate final BUDA results in ./recon/ folder.



Reference

If possible, please include the following citations if you find our reconstruction useful:

- [1] Liao C, Bilgic B, Tian Q, Stockmann JP, Cao X, Fan Q, Iyer SS, Wang F, Ngamsombat C, Lo WC, Manhard MK. Distortion-free, high-isotropic-resolution diffusion MRI with gSlider BUDA-EPI and multicoil dynamic B0 shimming. Magnetic Resonance in Medicine. 2021

- [2] Liao, C., Cao, X., Cho, J., Zhang, Z., Setsompop, K. and Bilgic, B., Highly efficient MRI through multi-shot echo planar imaging. In Wavelets and Sparsity XVIII (Vol. 11138, p. 1113818). International Society for Optics and Photonics. 2019