EE591 Project
Auto-calibrating SENSE

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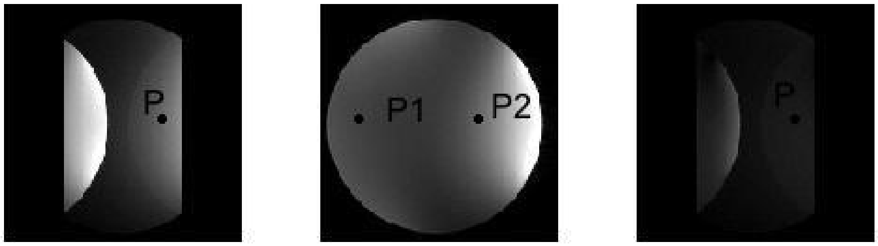
1 Introduction

The calibration of coil sensitivity maps is crucial in parallel imaging. The most common way to determine the sensitivity maps is obtaining low-resolution pre-scans. However this could lead to reconstruction errors if the object is not static, since the sensitivity functions are different between pre-scan and under-sampled scans.

In SMASH-like (SMASH: SiMultaneous Acquisition of Spatial Harmonics,[1]) parallel imaging, the reconstruction function can easily be calculated by fitting real-time data with a small number of additional k-space lines without knowing the exact coil sensitivity distribution. In SENSE-like (SENSE: SENSitivity Encoding,[2]) parallel imaging, sensitivity maps are always required in order to determine the reconstruction matrix. A number of difference approaches have been demonstrated which extract real-time coil sensitivity information from under-sampled data. The most direct method to do this is acquiring full data lines in the central region of k-space, then apply Fourier transform to get a no-aliasing low-resolution image. There are other methods like TSENSE [3], SHRUG (Self Hybrid Referencing with UNFOLD and GRAPPA)[4] which use temporal low-pass filter similar to UNFOLD [5] to remove aliased component from reduced FOV images.

In this project the above auto-calibration methods for SENSE were implemented on both phantom and *in vivo* experiments. Tests were also done on a created data set which simulated a time-varying object.

2 Methods



(a) (b) (c)

Figure 1: SENSE

SENSE

Parallel imaging techniques use the sensitivity differences of individual coils in a coil array to reduce the number of phase encoding in MR scans. For image domain techniques like SENSE, the basic concept is shown in Fig. 1. If we sampled the k-space in an interleaved pattern, we will get images with half the FOV and aliasing artifacts. In these aliased images of each coil, as Fig. 1 (a) & (c), point P is actually a linear combination of P_1 and P_2 from the original image, and the coefficients of this combination is determined by the respective coil sensitivity profile of each coil. The matrix formulation of SENSE reconstruction can be written as [2]

$$\mathbf{G} = \mathbf{E}\mathbf{f} + \mathbf{n} \tag{1}$$

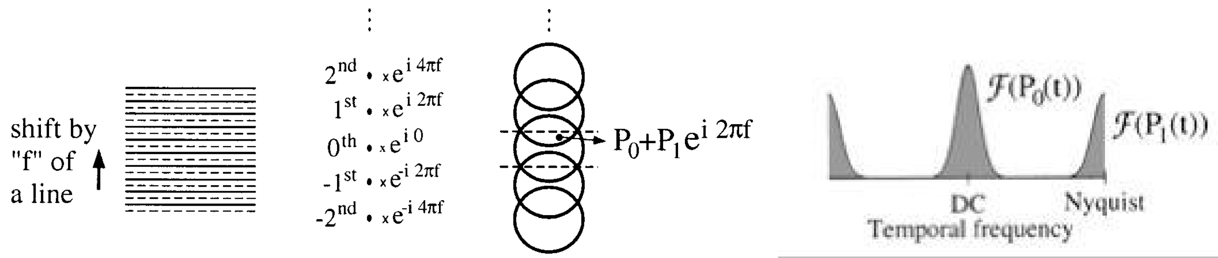
where $\mathbf{G}$ is the vector of measured k-space samples, $\mathbf{E}$ is the encoding matrix, $\mathbf{f}$ is the vector of magnetization image voxels, and $\mathbf{n}$ is coil noise. So the unaliased image $\hat{f}$ can be calculated by

$$\hat{f} = (\mathbf{E}^H \Psi^{-1} \mathbf{E})^{-1} \mathbf{E}^H \Psi^{-1} \mathbf{G} = \mathbf{U}\mathbf{G} \tag{2}$$

where Φ is the estimated noise correlation matrix between coils. In theory, an coil array of n channels can achieve an reduction factor of n in parallel imaging.

UNFOLD

As Fig. 2(a) shows, a shift of sampling function by a fraction f of a line lead to a linear phase shift of aliasing replicas except the central one. If we keep shifting the sampling



(a) (b)

Figure 2: UNFOLD *B.Madore,G.H.Glover,andN.J.Pelc,UNFOLD,Magn.Reson.Med.*,42:813828,1999

function of each time frame, the temporal frequency spectrum of each replica will also be shifted. As in Fig. 2(b), the signals from replica P_1 is shifted to the Nyquist frequency, and the signals of P_0 is centered around DC. Thus by applying a temporal low-pass filter we can eliminate the signals from aliasing component P_1, and then FFT the filtered spectrum back into time-domain to get a unaliased P_0 image [5].

TSENSE

The TSENSE estimate is defined as [3]

$$\hat{f}_{TSENSE}(x,y,t) = [\hat{f}_{SENSE}(x,y,t)]_{(1,1)} * h_{LPF}(t) = [\mathbf{U}\hat{f}_{UNFOLD}]_{(1,1)} \qquad (3)$$

In adaptive TSENSE, unaliased sensitivity maps are calculated from aliased images through temporal low-pass filtering. Then SENSE and UNFOLD are applied to remove aliasing artifacts.

SHRUG

The sampling pattern of TSENSE and SHRUG are shown in Fig. 3 [4]. In TSENSE, k-space lines are acquired every n lines in each frame. In SHRUG, the central region is sampled every other line, and more loosely in the outer region. As in Fig. 3c when reduction factor = 3, k-space data are sampled every 2 lines in the central 1/3 region and every 4 lines in the other parts, while TSENSE sampled one k-space line every three lines (Fig. 3b). In SHRUG, Data from the central region are used to determine coil sensitivity maps by temporal low-pass filtering, then variant-density SENSE is conducted to reconstruct full-FOV images before applying UNFOLD to suppress aliasing artifacts.

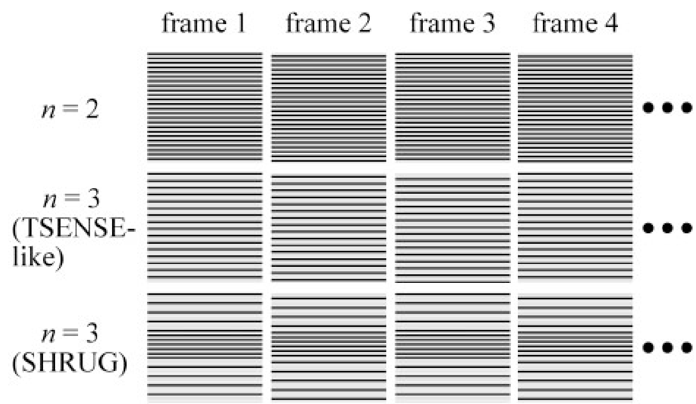


Figure 3: TSENSE and SHRUG (*B.Madore.Unfold−sense,Magn.Reson.Med.*,52:310−320,2004)

3 Results

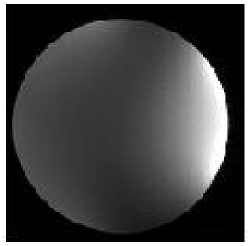
Phantom (static)

The phantom images were obtained by a four-element coil array. Phase encoding was conducted along the horizontal direction. The combined unaliased full-FOV image and aliased images (reduction factor = 2) of each coil are shown in Fig. 4. Fig. 5 and Fig. 6 are coil sensitivity maps calculated from the k-space central 1/8 data and temporal low-pass filtering, respectively. The reconstructed images are in Fig. 7. In reconstruction by reference lines images there are artifacts along phase encoding direction. Errors also occurred at where there is a sharp edge that low-resolution sensitivity maps failed to preserve.

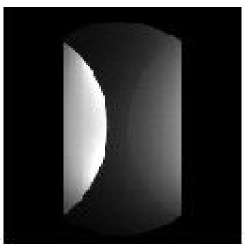
Head (static)

Head images were also obtained by a four-element coil array. The combined unaliased full-FOV image and aliased images (reduction factor = 2) of each coil are shown in Fig. 8. Fig. 9 and Fig. 10 are coil sensitivity maps calculated from the k-space central 1/8 data and temporal low-pass filtering, respectively. The reconstructed images are in Fig. 11.

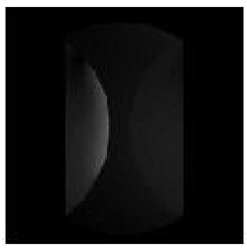
The same reconstruction process for reduction factor = 3 is shown in Fig. 12 to Fig. 15. TSENSE and SHRUG diverge when reduction factor is greater then 2.



(a) Combined Full FOV Image



(b) Coil 1

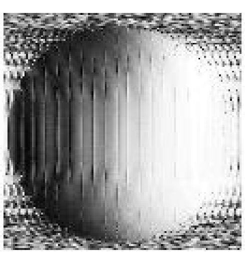


(c) Coil 2

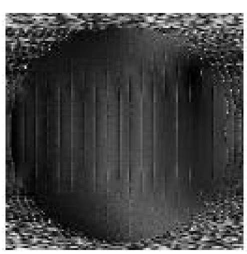
(d) Coil 3

(e) Coil 4

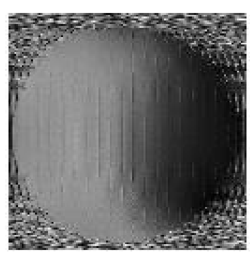
Figure 4: Phantom Images (reduction factor = 2)



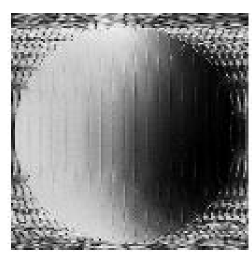
(a) Coil 1



(b) Coil 2

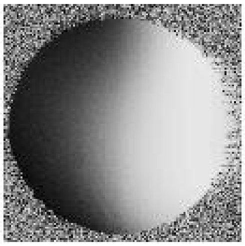


(c) Coil 3

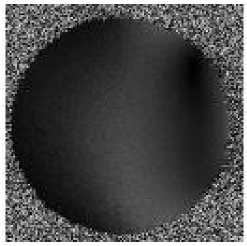


(d) Coil 4

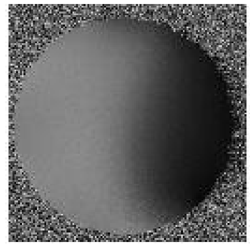
Figure 5: Coil Sensitivity Maps Calculated by 1/8 FOV Reference Lines



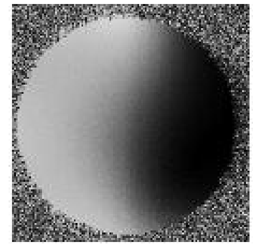
(a) Coil 1



(b) Coil 2

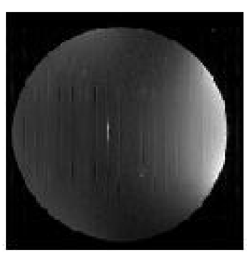


(c) Coil 3

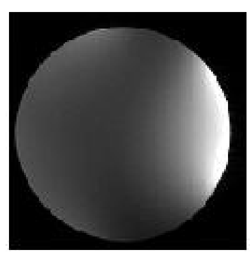


(d) Coil 4

Figure 6: Coil Sensitivity Maps Calculated by Temporal LPF (# of time frames = 32)

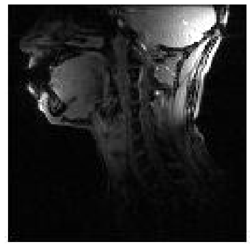


(a) 1/8 FOV Reference Lines



(b) TSENSE/SHRUG

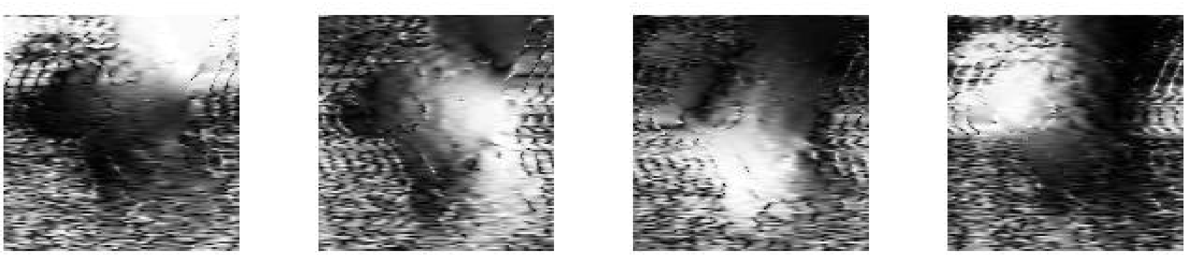
Figure 7: Reconstructed Images (reduction factor = 2)



(a) Combined Full FOV Image

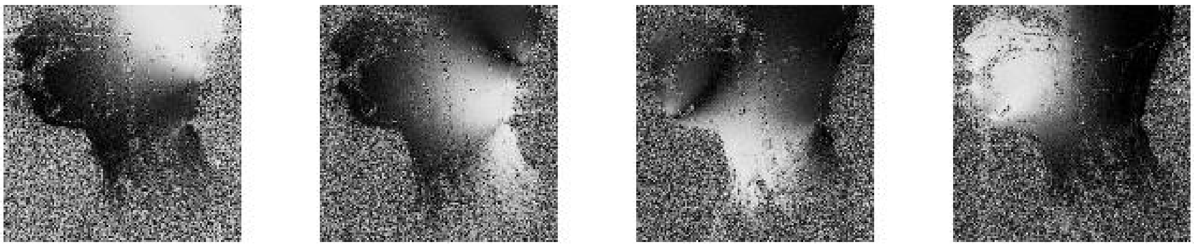
(b) Coil 1 (c) Coil 2 (d) Coil 3 (e) Coil 4

Figure 8: Head Images (reduction factor = 2)



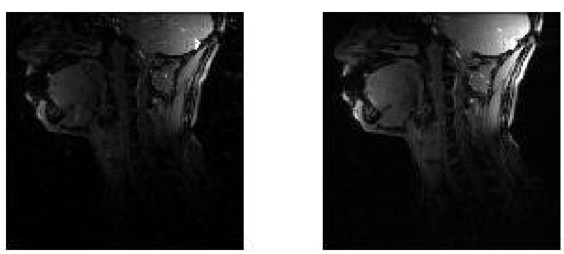
(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 9: Coil Sensitivity Maps Calculated by 1/8 FOV Reference Lines



(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 10: Coil Sensitivity Maps Calculated by Temporal LPF (# of time frames = 32)



(a) 1/8 FOV Reference Lines (b) TSENSE/SHRUG

Figure 11: Reconstructed Images (reduction factor = 2)

(a) Combined Full FOV Image

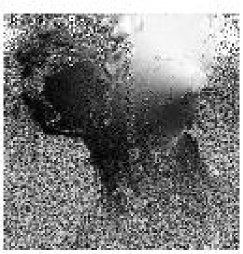
(b) Coil 1

(c) Coil 2

(d) Coil 3

(e) Coil 4

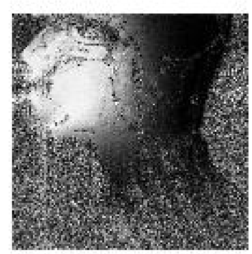
Figure 12: Head Images (reduction factor = 3)



(a) Coil 1

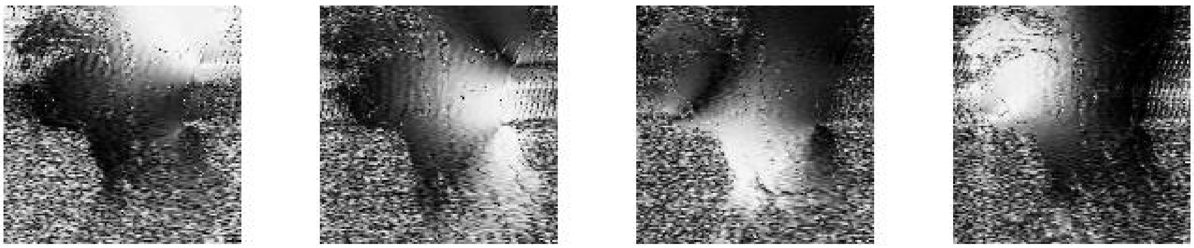
(b) Coil 2

(c) Coil 3



(d) Coil 4

Figure 13: Coil Sensitivity Maps Calculated by TSENSE (# of time frames = 32)



(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

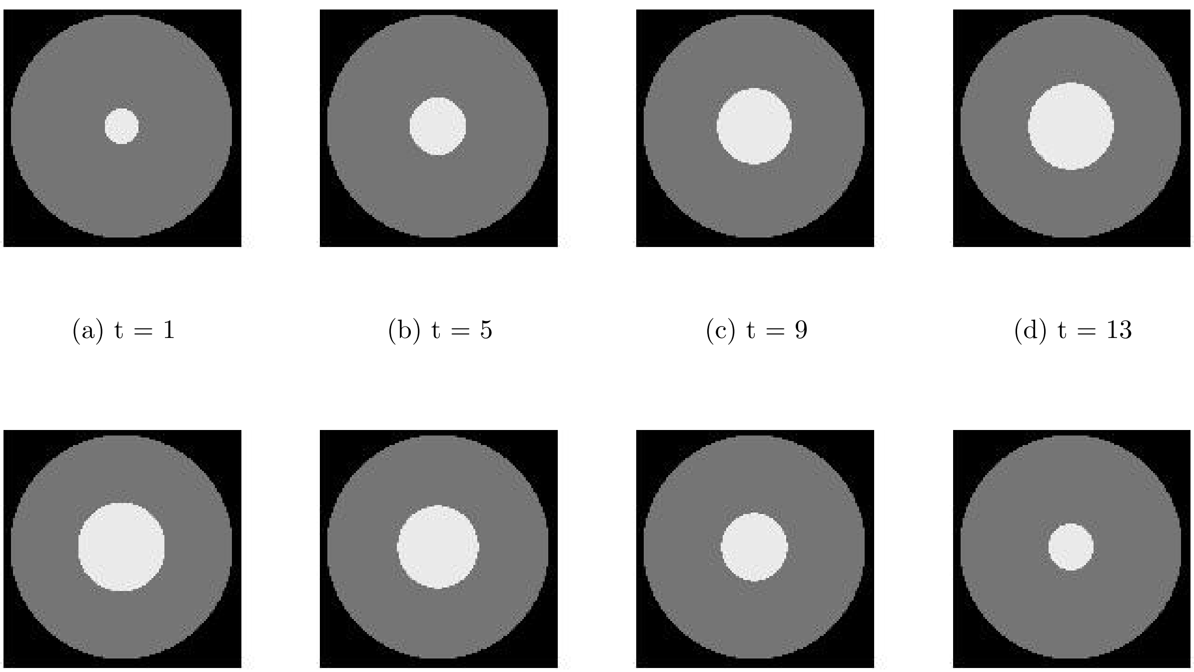
Figure 14: Coil Sensitivity Maps Calculated by SHRUG (# of time frames = 32)

(a) 1/8 FOV Reference Lines (b) TSENSE (c) SHRUG

Figure 15: Reconstructed Images (reduction factor = 3)

Simulated Phantom (dynamic)

A phantom was generated with a dynamic region near the image center and is static in the outer region. There are totally 32 time frames, a part of them are shown in Fig. 16. Coil sensitivity maps simulated using Biot-Savart law (Fig. 17) were used to generate aliased single-coil images (Fig. 18). Sensitivity profiles extrcted from undersampled data are shown in Fig. 19 and Fig. 20. For images reconstructed using reference lines, there are artifacts similar to Fig. 7(a). For images reconstructed using TSENSE and SHRUG, the smearing effect caused by temporal low-pass filtering was reflected as spatial blurring in the dynamic region of object domain. The 17th frame is at the center of the whole time-series, so it is not seriously affected by the smearing. In the edge of FOV there are aliased components that UNFOLD didn't completely remove. The reason is that in these areas the aliased replicas are more "dynamic", and their spectra extended into the low-frequency region and was partially preserved under the low-pass filter we applied.



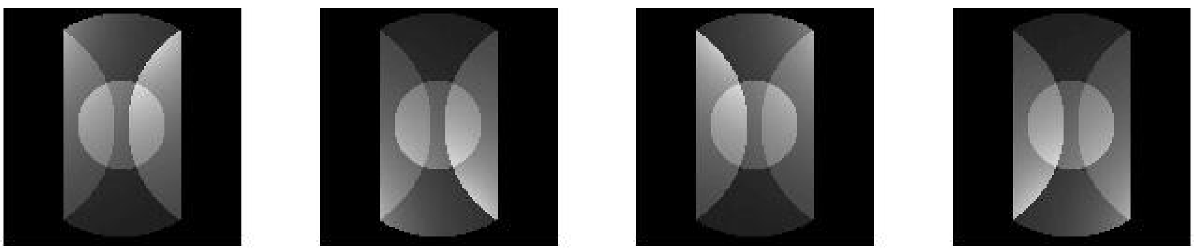
(a) t = 1 (b) t = 5 (c) t = 9 (d) t = 13

(e) t = 17 (f) t = 21 (g) t = 25 (h) t = 29

Figure 16: Simulated Dynamic Phantom (total # of time frames = 32)

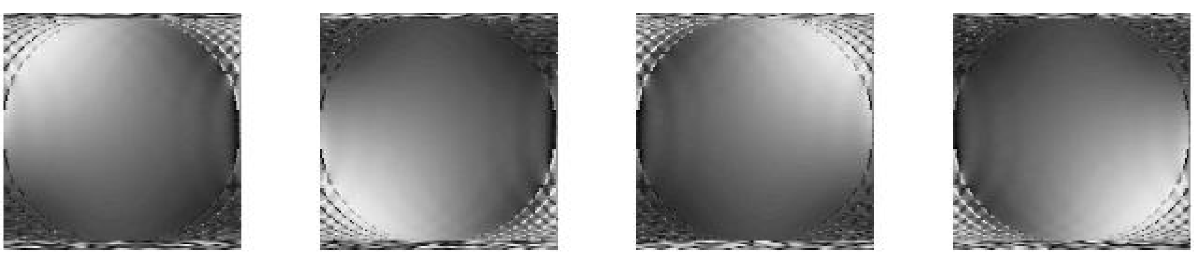
(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 17: Simulated Coil Sensitivity Maps



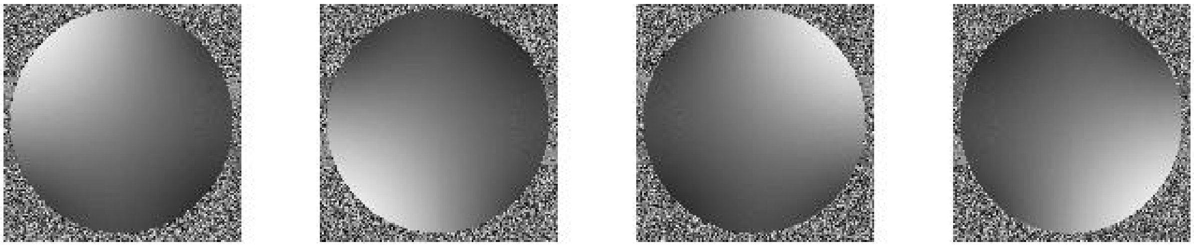
(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 18: Aliased Images (reduction factor = 2, t = 17)



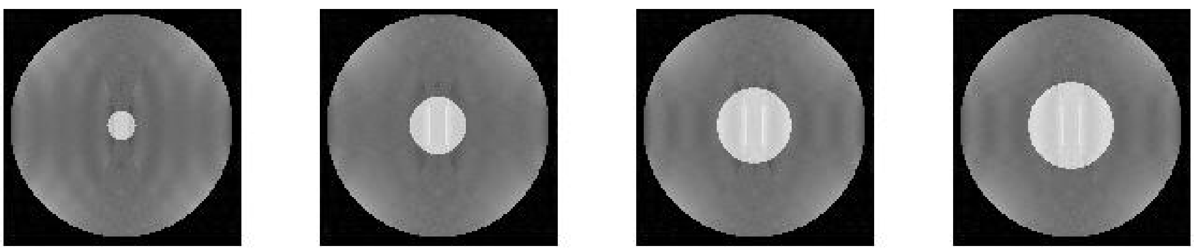
(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 19: Coil Sensitivity Maps Calculated by 1/8 FOV Reference Lines (t= 17)

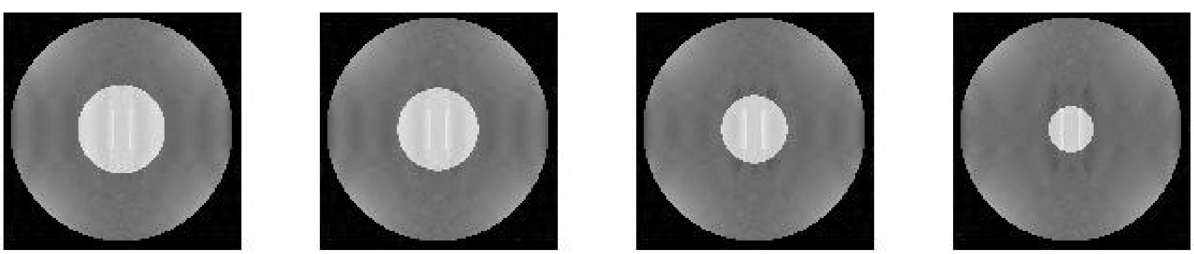


(a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

Figure 20: Coil Sensitivity Maps Calculated by Temporal LPF (t =17)

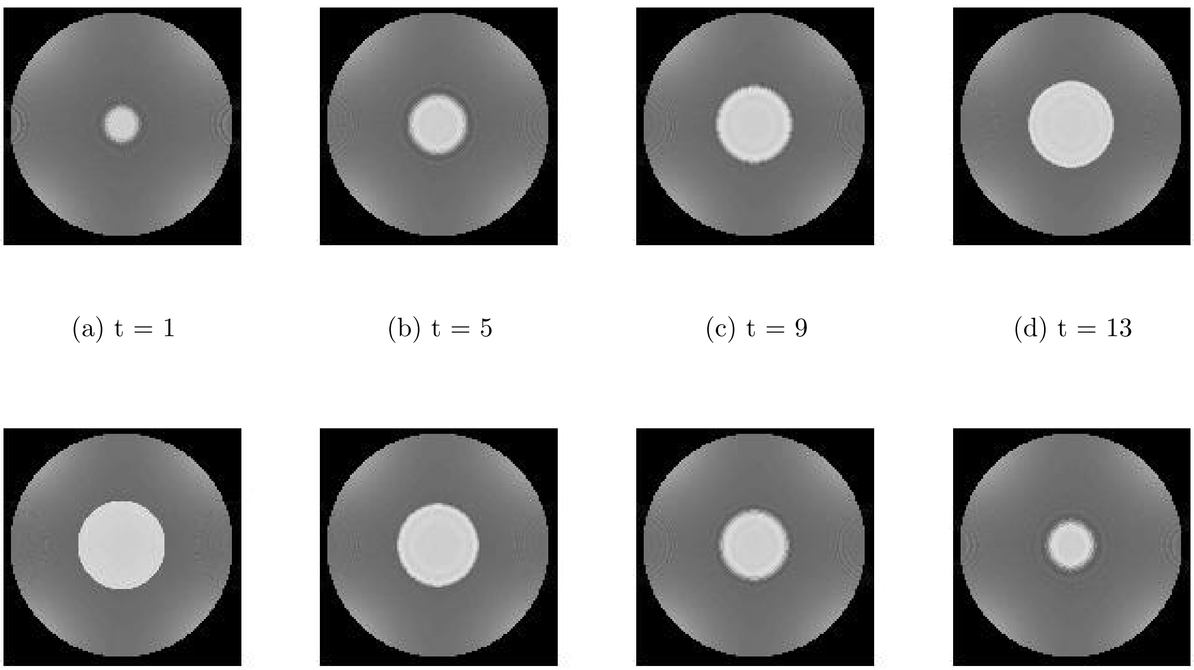


(a) t = 1 (b) t = 5 (c) t = 9 (d) t = 13



(e) t = 17 (f) t = 21 (g) t = 25 (h) t = 29

Figure 21: Reconstructed Images (1/8 FOV reference lines)



(a) t = 1 (b) t = 5 (c) t = 9 (d) t = 13

(e) t = 17 (f) t = 21 (g) t = 25 (h) t = 29

Figure 22: Reconstructed Images (TSENSE/SHRUG)

4 Discussion & Conclusion

In this project we demonstrated different methods for auto-calibrating SENSE: reference lines, TSENSE, and SHRUG. The advantage of extracting sensitivity profiles through temporal low-pass filtering over reference lines is the shorter scan time. As in the above results, we used the central 1/8 data lines to generate the low-resolution sensitivity maps, so the actual reduction factor of reference line SENSE is 1.78 while those of TSENSE and SHRUG are both 2.

Using temporal low-pass filtering to obtain sensitivity information for parallel reconstruction is an efficient approach since it doesn't require any additional data lines. However for rapidly varying objects the temporal smearing in sensitivity calibration caused by low-pass filtering may lead to reconstruction errors. So it is important to choose temporal filters carefully when calculating coil sensitivity maps.

TSENSE and SHRUG are identical when the reduction factor is two. For a reduction factor greater then two, elimination of aliased components in TSENSE tends to be more difficult because the spectra of different replicas are closer, making it harder to perfectly separate them. In our results (15) this effect was not apparent, instead we even got a more blurred image from SHRUG-SENSE reconstruction than TSENSE. This may because the spectrum bandwidth of slowly-varying components is narrow enough to avoid serious cross talk under a reduction factor of three, so we only see the blurring effect resulted from low-resolution sensitivity maps SHRUG created.

In TSENSE and SHRUG the UNFOLD method only contributes to sensitivity profiles calibration and artifacts suppression. If we combine UNFOLD and k-space based parallel imaging techniques like SMASH [6], with proper modifications it is possible to use UNFOLD to further increase acquisition speed for at least two-times.

References

[1] D. K. Sodickson and W. J. Manning. Simultaneous acquisition of spatial harmonics (smash). *Magn. Reson. Med.*, 38:591–603, 1997.

[2] K. P. Pruessmann, M. Weiger, M. B. Scheidegger, and P. Boesiger. Sense: Sensitivity encoding for fast mri. *Magn. Reson. Med.*, 42:952–962, 1999.

[3] P. Kellman, F. H. Epstein, and E. R. McVeigh. Adaptive sensitivity encoding incorporating temporal filtering (tsense). *Magn. Reson. Med.*, 45:846–852, 2001.

[4] B. Madore. Unfold-sense: A parallel mri method with self-calibration and artifact suppression. *Magn. Reson. Med.*, 52:310–320, 2004.

[5] B. Madore, G. H. Glover, and N. J. Pelc. Unaliasing by fourier-encoding the overlaps using the temporal dimension (unfold) applied to cardiac imaging and fmri. *Magn. Reson. Med.*, 42:813–828, 1999.

[6] Jeffrey Tsao. On the unfold method. *Magn. Reson. Med.*, 47:202–207, 2002.