# Two-Fold Phase Encoded SENSE Acceleration with a Single-Channel Coil

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**INTRODUCTION:** The purpose of this work is to add a two-fold acceleration SENSE-like acquisition method to the family of available acceleration methodologies for single RF coil systems. While SENSE requires spatial variation of receive coil sensitivities for image unaliasing (1), phase SENSE (P-SENSE) introduces the novel manipulation of spatial variation of magnetization phase of the object being imaged to replace the need for spatial variation of coil sensitivities. This method, in turn, relies upon the assumption of real valued reconstructed images, similar to partial-NEX reconstruction (2). The P-SENSE unaliasing technique in two-dimensions is mathematically equivalent to the separation of two simultaneously excited slices in the special case of reception with a single coil (3), where magnetization phase is manipulated in the direction of aliasing in both cases.

**OVERVIEW OF THE METHOD:** A modified two-fold accelerated SENSE acquisition is made, with the addition of a subset of Nyquist critically sampled $k_y$ lines in the center of *k*-space and a shift of all $k_y$ lines. The $k_y$ lines are shifted by $\Delta k_y$=0.5 by proper $G_y$ gradient encoding to create a spatial variation of magnetization phase in the direction of image aliasing by means of the Fourier shift theorem. This shift yields a phase that varies linearly in image-space by 180-degrees such that aliased voxels contain signal that differs in phase by 90 degrees. In gradient-recalled echo acquisitions, slight reshimming in the y-direction may also be used. The Nyquist critically sampled *k*-space lines are extracted as a low spatial resolution reference image of the spatial variation of phase.

Image unaliasing proceeds by extending the assumption of a real-valued reconstructed image, common in partial-NEX imaging, to the SENSE equation. The SENSE equation is over determined if an array of receive coils is utilized. The over determined system allows the sub-sampling of *k*-space in parallel imaging. A real-valued isomorphism of the complex-valued SENSE method is shown in the below matrix equations, where ***b*** is a vector of the aliased complex image data from one coil, ***x*** is a vector of the true unaliased complex image data, and **A** is the SENSE encoding matrix including the magnitude, **S**, and phase, **θ**, of the known coil sensitivity profile in the voxels that are aliased. In the case of P-SENSE, the assumption of a real-valued reconstructed image halves the number of elements of the reconstructed image vector by eliminating the even elements of the ideal image, ***x***, and the even columns of the encoding matrix, **A**, thereby yielding an over determined set of equations even if a single coil is utilized. Further, with a single coil the sensitivity map is set to unity while the phase is extracted from the low spatial resolution map. As in the method described in (3), the drawback of this method is that the generation of the unaliased image may occasionally rely upon the solution of an ill-conditioned system of equations. Thus, if aliased voxels differ in phase by n*180 degrees, unaliasing is not possible with a single coil.

**EXPERIMENTAL METHODS:** The study was performed on a GE Signa EXCITE 3 T MR scanner. A gradient-recalled echo sequence was used, and acquisition was done off-line using a computer equipped with three Mercury ECDR-GC316 cards (4) running Linux OS. A quadrature head coil was used and the acquisition parameters were: TR 17 ms (phantom)/350 ms (head), TE 7.2 ms, BW 32.25 kHz, FOV 24 cm (phantom)/22 cm (head), slice thickness 3 mm, 256x256 reconstructed matrix, reduction factor 2, and number of critically sampled lines 50 (phantom)/100 (head) yielding acceleration factors 1.67 (phantom)/1.44 (head).

$$\begin{pmatrix} \cos(\theta_1)S_1 & -\sin(\theta_1)S_1 & \cos(\theta_2)S_2 & -\sin\theta_2 S_2 \\ \sin(\theta_1)S_1 & \cos(\theta_1)S_1 & \sin(\theta_2)S_2 & \cos(\theta_2)S_2 \end{pmatrix} \begin{pmatrix} x_{1R} \\ x_{1I} \\ x_{2R} \\ x_{2I} \end{pmatrix} = \begin{pmatrix} b_R \\ b_I \end{pmatrix}$$

$$\mathbf{A}\cdot\boldsymbol{x}=\boldsymbol{b}$$

**RESULTS and DISCUSSION:** Results from the phantom study are shown in Fig. 1, and the human study are shown in Fig. 2. Figures 1A and 2A illustrate the ideal image; 1B and 2B, the smoothed low resolution reference image magnitude; 1C and 2C, the combined low resolution phase reference image; 1D and 2D, the acquired aliased image; 1E and 2E, the reconstructed unaliased image; 1F and 2F, the noise corrected unaliased image. As seen in Fig. 1E, the areas of the image that are aliased with noise exhibit noise amplification due to low values of the determinant of the encoding matrix. Altering the singularity threshold in the SVD algorithm for matrix inversion can reduce this noise, but simultaneously decreases overall image quality (5).

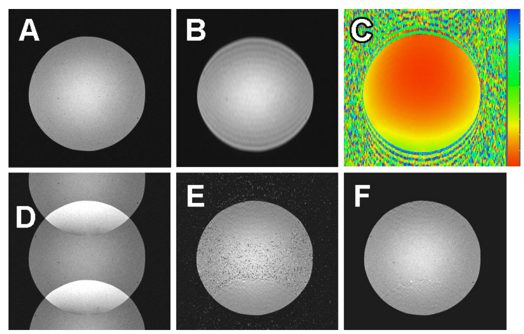


***Fig.1.*** *A: Ideal phantom; B: reference; C: phase; D: aliased; E: noise-uncorrected; F: noise-corrected images.*

To create Fig. 1F, a twofold reconstruction process was utilized. First, smoothed amplitude and phase reference maps were created. Next, similar unsmoothed maps were created. The final phase map was combined from the two maps using a 15% threshold of the smoothed reference amplitude image. In areas above the threshold, smoothed phase data were replaced by unsmoothed. From this combined map, matrix **A** was created. Additionally, in pixels where the amplitude of the reference image was below 10%, the equivalent elements of matrix **A** were set to zero to take advantage of the SVD algorithm feature that eliminates singularities. In pixels where the second column of matrix **A** had zero values, the amplitude of ***b*** was copied to the top image half $\boldsymbol{x}_{1R}$. Similarly, the bottom half $\boldsymbol{x}_{2R}$ was created when the first column had zero values. It must be noted that in such pixels the determinant of **A** is zero and the use of the inverse matrix $\mathbf{A}^{-1}$ to solve equations is futile. The SVD algorithm treats such areas with reduced *rank* of the matrix **A** accordingly, leading to the expected solutions. The byproduct of this procedure is a substantial elimination of noise from the areas outside the phantom, which is good. The improved algorithm works properly when the whole *k*-space is used for computation. In sub-processing, the unused *k*-space rows were filled with zeroes, and for this reason, the image in Figs. 1D and 2D are square rather than rectangular, as is usually presented. Few regions of ill-conditioned systems of equations arise from the skin around the brain, resulting in minor artifact in Figs. 2E and 2F.

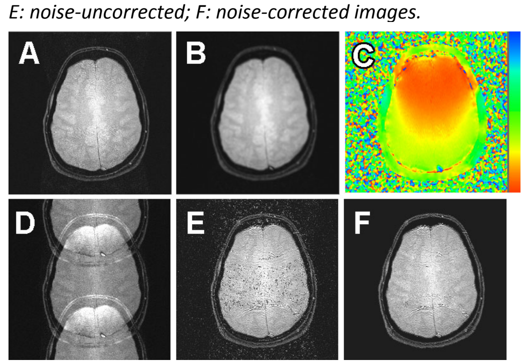


***Fig.2.*** *A: Ideal head; B: reference; C: phase; D: aliased; E: noise-uncorrected; F: noise-corrected images.*

**CONCLUSION:** This abstract shows that when assuming a real-valued reconstructed image, sensitivity encoding can be performed, utilizing the phase of the acquired image even if the receiver sensitivity is uniform. From the study of multi-slice, simultaneous acquisition with multiple RF coils (3), we learned the importance of using magnetization phase-encoding in addition to RF coil profiles. Even when all of the coil profiles were set to one, the separated slices were better than when using actual profiles without phase-encoding. The same applies to the SENSE method with an arbitrary number of coils. The addition of magnetization phase-encoding doubles the number of useful, nonsingular equations and increases the quality of unaliased images. In a multicoil environment, final images can be obtained in the complex form and further processing like half-NEX and/or multi-slice excitation can be combined with the SENSE method.

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