

# Gradient Linear System Modeling using Gradient Characterization

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## Introduction:

Spiral imaging and echo-planar imaging require fast and strong gradients with high fidelity. Gradient characterization [1-4] provides a tool for distortion correction based on calibration measurements. Among the proposed techniques are so-called self-encode (SE) methods [4-6] and off-center slice selection (DSS) method [7-8]. A recently proposed algorithm, self encoded slice selection (SESS), combines these two methods [9]. The new approach takes advantage of the SE method's flexibility of characterizing waveform gradients with maximum gradient amplitude and maximum slew rate and the DSS method's short data acquisition time. Here, we apply the hybrid technique to model gradient systems as a linear time-invariant transfer function,  $H(f)$ , through a frequency-domain analysis and a time-domain analysis [10,11]. The  $H(f)$  model of the gradient system on the 3T Siemens MAGNETOM Trio, a TIM system, scanner is presented here along with the characterization and analysis of common waveform gradients.

## Methods:

The SESS algorithm requires a minor modification to the DSS method if the maximum  $k$ -space value of the test waveform gradient,  $k_{max}$ , is greater than the first zero crossing,  $k_{zc}$ . The SESS is similar to the DSS method: exciting off-isocenter slices on a large phantom with and without the test waveform gradients. Any time-varying distortions can be measured by comparing the two measurements and extracting a constant phase term. During the case when  $k_{max} > k_{zc}$ , self-encode gradients are used to shift the waveform so that different pieces of the test gradient can be characterized with higher SNR. By ensuring that there is sufficient overlap between the measured pieces, the final measurement can be obtained through splicing the segments together.

Four different slice locations (-50, -40, +40 and +50mm) were used to excite a 3mm-thick slice, and least-squares estimation of extracting the same waveform from different slices was used for robustness. A 170mm spherical phantom filled with 1.25g NiSO<sub>4</sub> 4H<sub>2</sub>O per 1000g of H<sub>2</sub>O was used on the Siemen Trio platform, with gradient waveforms designed for an effective maximum amplitude and slew rate of 40mT/m and 170T/m/s. A TE of 16ms and a TR of 300ms were used for each scan with a readout bandwidth of 200Hz/pixel.

The SESS method was used to model  $H(f)$  through a frequency-domain approach. 76 sinusoid gradients (frequencies logarithmically spaced apart in the range of 150Hz to 6000Hz) were measured. The sinusoid waveform gradients were designed to achieve either the maximum amplitude or slew rate.

## Results and Discussion:

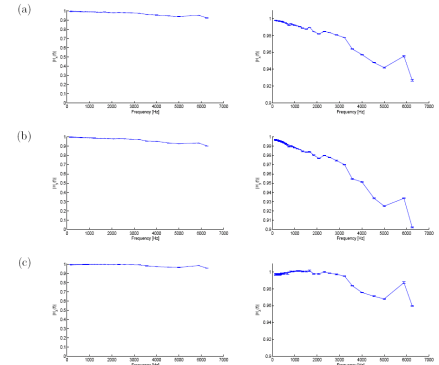
$H(f)$  was measured for the three different gradient axis (Fig 1, 2). That result was validated through measuring  $H(f)$  using the SE gradient characterization algorithm. To find  $H(f)$  with time-varying phase corrections, it took ~20min for the SE method and ~5min for the SESS method – a compelling advantage for the SESS algorithm. Note that the DSE algorithm could not be used due to the algorithm's limitation of insufficient  $k$ -space range. For low frequencies,  $H(f)$  can be accurately determined. However, at higher frequencies, the frequency samples are further spaced apart for the frequency-domain approach. The estimated  $H(f)$  was used to predict actual waveform gradients given the ideal input and compared to the measured result using the SESS algorithm (Fig 3, 4). As seen in the figures, the gradient system does an excellent job of correcting any distortions and output a sufficient waveform gradient. The main deviation appears as a linear time-delay. Additionally,  $H(f)$  provides for a good model for predicting any inadequacies.

## Conclusion:

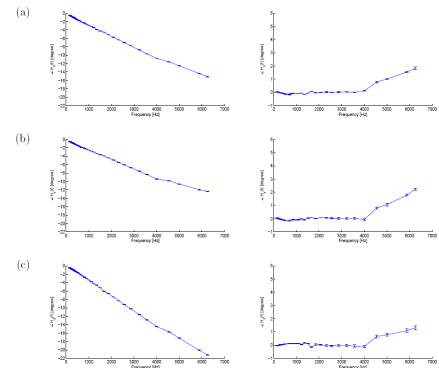
The recently presented SESS algorithm for gradient characterization has favorable properties in acquisition speed and characterization accuracy. Future work on linear-systems modeling will address improved sampling of higher frequencies with non-integer sinusoidal or in combination with time-domain approaches.

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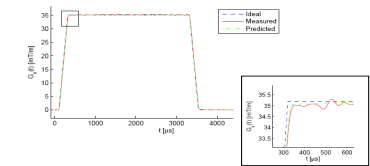
**References:** [1] Spielman and Pauly, MRM, 34:580–585, 1995. [2] Tan and Meyer, ISMRM, 981, 2007. [3] Mason et al, MRM, 38:492–496, 1997. [4] Onodera et al, Journal of physics E, 20:416–419, 1987. [5] Takahashi and Peters, MRM, 34:446–456, 1995. [6] Alley et al, MRM, 39:581–587, 1998. [7] Duyn et al, JMR, 132:150–153, 1998. [8] Zhang et al, MRM 39:999–1004, 1998. [8] Kim and Spielman, MRM, 56:198–203, 2006. [9] Beaumont et al, MRM, 58:200–205, 2007. [10] Kerr. PhD thesis, Stanford University, 1998. [11] Kerr and Pauly, Patent No 690528, 1999.



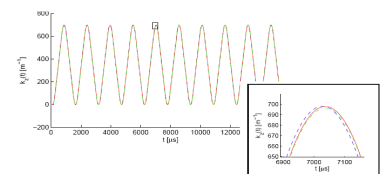
**Fig 1:**  $|H(f)|$ : (a) x-axis, (b) y-axis, and (c) z-axis; (left) regular view and (right) zoomed view.



**Fig 2:** Phase of  $H(f)$ : (a) x-axis, (b) y-axis, and (c) z-axis; (left) regular view and (right) linear component removed.



**Fig 3:** Ideal, measured, and predicted box waveform gradient on the x-axis.



**Fig 4:** Ideal, measured, and predicted EPI waveform gradient on the z-axis.