Introduction
Unwanted magnetic fields resulting from eddy currents are detrimental for MR imaging and localized spectroscopy. A linear system model for the field gradient assumes that a system impulse response $h_S(t)$ determines the output field gradient $G_{output}$ from the input waveform $G_{input}$ by

$$G_{output}(t) = G_{input}(t)^* h_S(t), \quad [1]$$

where the $*$ denotes convolution. Acceptable $G_{output}$ distortion is typically obtained by waveform pre-emphasis (1), which is equivalent to setting

$$G_{input}(t) = G_{ideal}(t)^* h_{P}(t), \quad [2]$$

where $h_{P}(t)$ is the pre-emphasis impulse response. The goal is to choose $h_{P}(t)^* h_{S}(t) = \delta(t)$ so that $G_{output}(t) = G_{ideal}(t)$. Gradient field distortion is frequently assumed to originate entirely from eddy currents described by a multi-exponential impulse response given by

$$h_{S}(t) = \delta(t) + \sum_k \alpha_k e^{-\tau_k t}, \quad [3]$$

where $\alpha_k$ and $\tau_k$ are amplitudes and time constants respectively. The corresponding pre-emphasis impulse response is then

$$h_{P}(t) = \delta(t) + \sum_k \beta_k e^{-\mu_k t}, \quad [4]$$

where $\beta_k$ and $\mu_k$ are determined by measuring $G_{output}$ for a single waveform $G_{ideal}$ fitting to obtain $\alpha_k$ and $\tau_k$, and using the requirement that $G_{output} = G_{ideal}$. The resulting pre-emphasis is assumed to correct all waveforms.

We have found that Eqs. [1] and [3] are not always valid because of short term non-linear effects within the gradient driver and non-eddy-current effects within the gradient coil. These effects cause gradient field distortion which is very difficult to separate from distortion due to eddy currents. The result is that short term gradient field distortion is not accurately measured and therefore not optimally compensated. Pre-emphasis determined based on a single waveform $G_{ideal}$ is not optimal for other waveforms.

Methods
Since true eddy current effects do follow Eq. [3] for $h_{S}(t)$, it is useful to retain the exponential pre-emphasis model in Eq. [4] for $h_{P}(t)$. To more accurately calculate pre-emphasis parameters in the presence of short term non-linear gradient driver and gradient coil errors, $\beta_k$ and $\mu_k$ can be thought of as "knobs" which can be varied to minimize $G_{error}$ for a plurality of waveforms $G_{ideal}$, where

$$G_{error}(t, \beta_1, \mu_1, \beta_2, \mu_2, \ldots) = G_{output} - G_{ideal}, \quad [5]$$

Response surface methodology (RSM) (2) can be used to efficiently sample and calculate $\beta_k$ and $\mu_k$ which minimize $G_{error}$. RSM is used in the empirical study of relationships between measured responses and a number of input variables, and is used to determine what input values yield a maximum or minimum for a specific response. RSM is especially useful when an exact model of the system response is unknown because the system interactions are too complicated to compute analytically. In our experiment, a number of responses are measured simultaneously for each setting of a group of the input variables $\beta_k$ and $\mu_k$ (multi-response experiment).

$G_{output}$ was measured on a commercial scanner (GE Medical Systems, Milwaukee, WI) at three points during the trapezoid plateau (beginning, middle and end) using a small doped water sample at two known x, y and z locations (+/- 10 cm). Trapezoidal waveforms with four different ramp times with the same amplitude were used for $G_{ideal}$ in our experiment. Three pairs of $\beta_k$ and $\mu_k$ (6 parameters) were varied in 53 separate combinations which were determined using RSM. Data acquisition to measure $G_{output}$ for all combinations took about 30 minutes for each ramp time. The difference $G_{error}$ was fit to a full quadratic polynomial of the 6 parameters (27 terms) for each ramp time and each plateau time. After the polynomial coefficients were determined, optimal $\beta_k$ and $\mu_k$ were calculated by minimizing $G_{error}$ summed at the three plateau points for each ramp time using non-linear optimization software.

Results
Fig. 1 shows the field near the trapezoid plateau for pre-emphasized waveforms. The pre-emphasis is calculated (a) by fitting $G_{output}$ to Eqs. [1] and [3] to determine $\alpha_k$ and $\tau_k$, and (b) using the RSM method outlined above. The RSM optimized pre-emphasis gives less overshoot and is more accurate during the interval after the ascending ramp. slowed is not available.

Conclusion
Gradient driver non-linearity and gradient coil errors complicate pre-emphasis calculation. Pre-emphasis parameters can be thought of as "knobs" which can be varied to minimize eddy current waveform distortion. Response surface methodology is a technique for efficiently finding the optimal parameter settings. The method is useful if analytical models for non- eddy--current distortion are unavailable.

References

Fig. 1. Z gradient field (% of maximum) vs. time (msec) with (a) conventional and (b) RSM pre-emphasis for 184 usec and 92 usec ramps.