Concurrent Monitoring of RF and Gradient Waveforms of Parallel Transmission Pulses by a Field Camera

David O Brunner[1], Benjamin E Dietrich[1], Mustafa Cavusoglu[1], Christoph Barmet[1,2], Bertram Wilm[1], and Klaas P Pruessmann[1]
[1]*Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Zurich, Switzerland,* [2]*Skope Magnetic Resonance Technologies, Zurich, Switzerland*

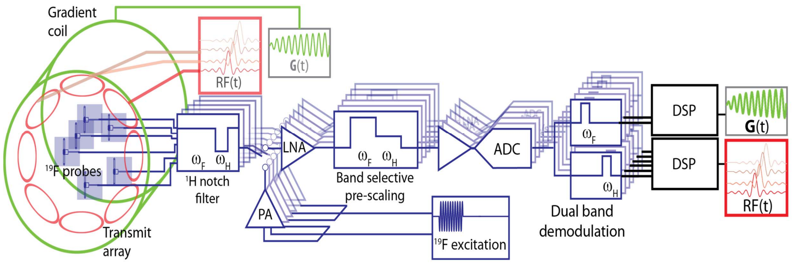

Figure 1: Schematic of the setup

Introduction: Advanced schemes of parallel excitation build upon the close and accurate interplay between several RF channels and gradient waveforms. We present a method based on gradient magnetic field monitoring[1] to measure the temporal evolution of both, the gradient magnetic field (in principle to higher orders) and the RF excitation pulses played by multiple transmit channels fully concurrently and at full power.

Hardware: The gradient induced field evolution was measured using 16 ^{19}F compound based field probes that where excited once at the beginning of the pulse to be monitored. Although each probe was equipped with a low-eddy current coaxial RF shield keeping the RF coupling from the transmitters below destructive limits, the receivers had to be equipped with narrowband filters before each gain stage, attenuating the signals in the ^{1}H band (20 to 40 dB) and having a low insertion loss (~0.85 dB) in the ^{19}F band, thus avoiding compression of the receiver chain. By this the stray coupled proton excitation pulses and the fluorine probe signals had a similar dynamic range and could be digitized by a single high-speed converter using a dual digital demodulation scheme[2] avoiding saturation effects. The monitored scanner was an Achieva 7T (Philips Healthcare, Cleveland, USA) system equipped with an 8 channel parallel transmit system (MultiX, Philips Research Laboratories, Hamburg, Germany).

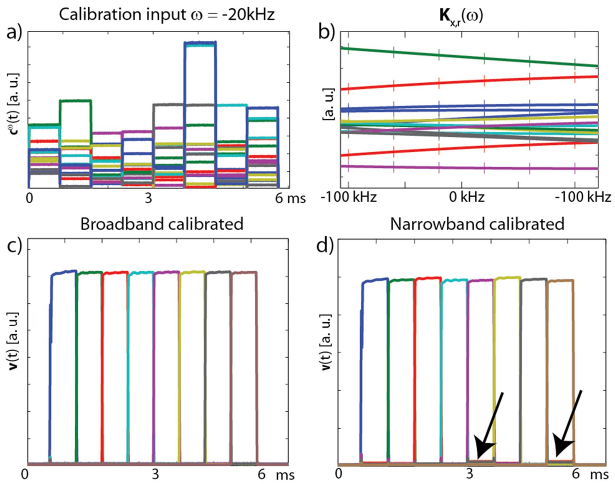

Figure 2: Signal processing; a) retrieved signals on RX channels c, b) frequency dependence of decoupling (cross measured, solid second order polynomial fit), c), d) retrieved TX signals showing the benefit of the broadband calibration approach (arrows show deficient disentanglement of the TX channels).

Signal processing: The linear coupling of RF signals from each port of the transmit array to the channels of the monitoring system has to be probed over the frequency span of the excitation to disentangle superimposed transmit signals of each TX channel (x) on the receive lines (r). To this end, short block pulses sent with each channel subsequently are recorded by each channel of the camera (Fig. 2a) and repeated shifted by 40 kHz steps. Each calibration pulse is stored in a time vector ($\mathbf{c}^{\boldsymbol{\omega},\mathbf{x}}_{\tau,\mathrm{r}}$) and requested amplitudes of each port in the rows of the matrix $\mathbf{P}^{\boldsymbol{\omega}}$. The coupling spectrum ($\boldsymbol{C}^{\omega}_{r,t}$) is then estimated by:

$$(\mathbf{A}_{\omega})_{\mathrm{i,r}} := \left(\mathbf{c}^{\boldsymbol{\omega},1}_{\tau,\mathrm{r}} \ldots \mathbf{c}^{\boldsymbol{\omega},\mathrm{x}}_{\tau,\mathrm{r}} \ldots \mathbf{c}^{\boldsymbol{\omega},\mathrm{n}}_{\tau,\mathrm{r}}\right) \Rightarrow \boldsymbol{C}^{\omega}_{r,x} = (\mathbf{A}^{\mathrm{H}}_{\omega}\mathbf{P}^{\boldsymbol{\omega}})^{\dagger}\mathbf{A}^{\mathrm{H}}_{\omega}\mathbf{A}_{\omega}.$$

Due to the smooth frequency domain behavior of the decoupling (Fig2.b), short time domain convolution kernels can be found: $\left(\mathbf{K}_{\mathrm{x,r}}\right)_{\tau'} = \mathrm{FT}\left(\mathbf{K}_{\mathrm{x,r}}(\boldsymbol{\omega})\right) = \mathrm{FT}\left(\left(\boldsymbol{C}^{\omega}_{r,x}\right)^{\dagger}\right)$, yielding the individual TX channels RF waveform by: $\mathbf{v}_{\tau,\mathrm{x}} = \sum_{\mathrm{r}}\sum_{\tau'}\left(\mathbf{K}_{\mathrm{x,r}}\right)_{\tau'} \cdot \mathbf{m}_{\boldsymbol{\tau}-\boldsymbol{\tau}',\mathbf{r}}$

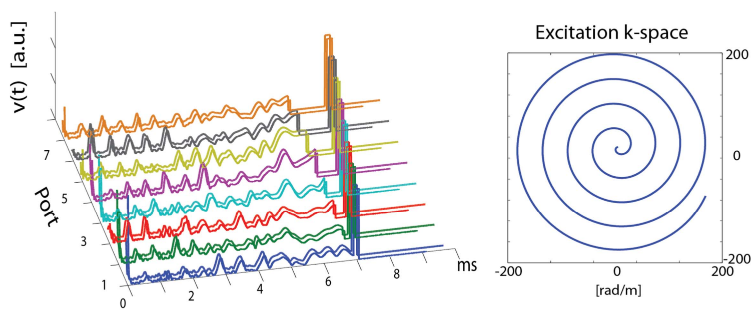

Figure 3: Comprehensive monitoring of a parallel excitation pulse. Left: Measured (in front) and requested (same color, behind) RF waveforms of all channels (blue-brown). Right: Concurrently measured excitation k-space trajectory.

The gradient waveforms are acquired and processed in independent data streams as shown in[1]. The excitation k-space trajectory ($\mathbf{k}_{\mathrm{ex}}(\mathrm{t})$) can be calculated from the receive trajectory ($\mathbf{k}_{\mathrm{rec}}(\mathrm{t})$) obtained from the field probes by: $\mathbf{k}_{\mathrm{ex}}(\mathrm{t}) = \mathbf{k}_{\mathrm{rec}}(\mathrm{T}) - \mathbf{k}_{\mathrm{rec}}(\mathrm{t})$ whereas T is the end time of the pulse.

Results: Fig.2c) shows an example of a calibration pulse series sent at +20 kHz offset to a calibration frequency showing that the individual transmit channels can be disentangled and scaled properly. Performing only one calibration train at -20 kHz difference to the evaluated pulse train shows artifacts (Fig.2d arrows) not separating the transmit channels correctly by several percent in magnitude. Fig.3 shows the monitoring of a spatially selective 2 times accelerated parallel excitation pulse monitoring the excitation k-space and the RF waveforms on equal time basis. The RF waveforms exhibit good relative correspondence to the requested waveform.

Discussion: Monitoring of parallel RF excitation pulses and in principle higher-order gradient field evolutions allows comprehensive description of the spin dynamics even in to date most complex MR systems. Although retrospective correction of the inaccuracies of the excitation process cannot be corrected as generically by reconstruction approaches as it is the case when monitoring gradient waveforms and field fluctuations during signal reception, many applications can be based on the additional information from an independent and comprehensive NMR monitoring system such as: timing optimization of multi-dimensional selective pulses, system stability testing, failure search, linearization and correction by pre-distortion of both RF and gradient chains, testing of coil high voltage withstanding and many more. No additional pick-up loops[3] or current sensors[4] need to be installed on the coil array omitting the necessity for such design considerations. However absolute quantification is estimated to be harder and the requirement for the stability of the electromagnetic boundary conditions is potentially higher than with the latter approaches. But very high accuracy in the temporal alignment of the RF and gradient waveforms is delivered since both are received by the same receiver commonly timed and with identical digital processing steps. Only the group delay of the analog receive chain adds a distortion between the bands, however these can be measured and calibrated on the bench. In principle the shown approach of monitoring parallel RF transmission can also be combined with continuous monitoring approaches[2] and can be performed concurrently with the experiment.

References: 1) Barmet et al. MRM 2008; 2) Dietrich et al. ISMRM 2012, 3) Graesslin et al. ISMRM RF Safety Workshop 2008, 4) Stang et al. ISMRM 2008