Field Monitoring During High-Power Transmission Pulses: A Digital Noise Cancelling Approach

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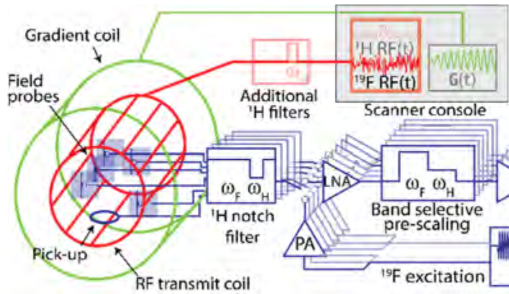
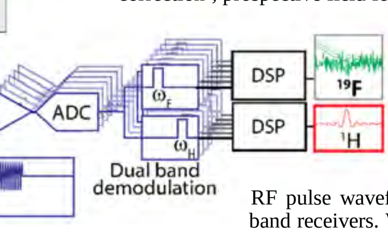

Figure 1: Setup

Introduction: Recordings of magnetic fields produced by gradient systems, main magnets or induced by the sample have been shown to greatly enhance the results and robustness of MR acquisitions by post-correction[1], prospective field feed-back approaches[2] or by serving as basis for enhanced system calibrations. Recently, the concurrent recording of RF pulse waveforms along with low-frequency field measurements has been introduced delivering the full information about the sequence as performed by the scanner[3]. The signals of the ^{19}F NMR based field sensors could be acquired without noticeable distortion or saturation induced by the high power pulses emitted by the scanner by use of narrowband filters and high dynamic range receiver chains (Fig. 1). Further, the RF pulse waveform could be acquired along using the same physical broad-band receivers. While the high power signal emitted in the ^{1}H band can be kept from affecting the field measurement in the ^{19}F band it was found that the noise floor in the ^{19}F band is significantly increased by the broadband noise and spur levels found at the output of typical high-power RF amplifiers which is coupled into the field probes. Therefore, stop-band filters had to be previously introduced into the transmission path of the scanner in order to stop the noise at the fluorine frequency. Although such filters are common pieces of technology they nevertheless introduce additional delays and losses and can introduce thermal drift behaviour. In this work we present an approach digitally compensating the noise contribution from the power amplifier which obsoletes largely the high power filters and most importantly allows measuring the system in its native configuration.

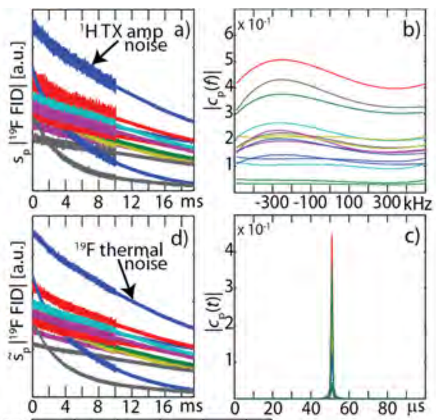
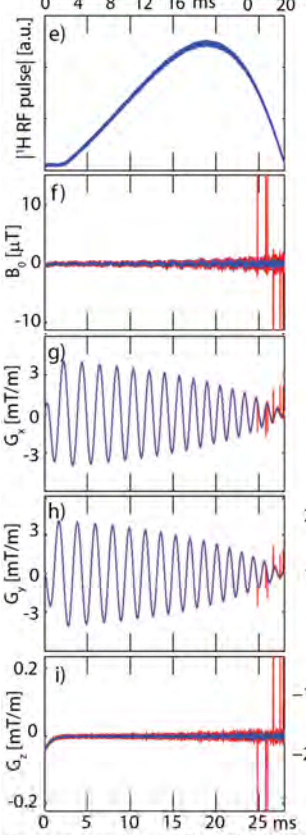
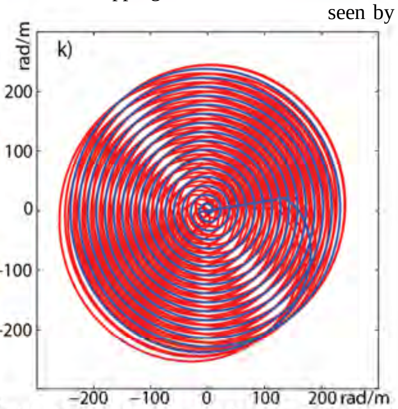

Figure 2: Results, a) FIDs with TX amplifier noise, b) spectrum of relative weights of the noise coupling and resulting filter c). d) FIDs with subtracted noise, monitored RF pulse e), fields f-i) and k-space trajectory k) for raw (blue) and denoised (red) case.

Methods: The noise at the output of the power amplifier can be regarded as an externally induced signal $\eta_{amp}(t)$ coupled into the field probes p with a complex weight $c_p(\omega)$ onto the FID. These coupling constants are considered as frequency dependent since some of the involved components such as tuned coils and signal conditioning filters are narrow-band. Therefore the signal present in the probe is in Fourier domain:

$$s_p(\omega) = FID(\omega) + c_p(\omega) \cdot \eta_{amp}(\omega) + \eta_{thermal}(\omega)$$

Recording the signal of a pick-up loop concurrently with the field probe data yields $s_{pu}(t) \propto \eta_{amp}(t)$ and can hence be used to subtract the noise of the power amplifier out of the FIDs. The corresponding complex weightings are obtained from the noise covariance in a calibration acquisition in which an ^{1}H RF pulse but no FID is excited in the probes: $c_p = \langle s_{pu}, s_p \rangle / \langle s_{pu}, s_{pu} \rangle$,

where $<,>$denotes a covariance.

The frequency dependency is obtained in Fourier domain binned to 100 equally wide bands. The spectra of the weightings are then fitted by a fourth order polynomial and transposed into a 100 tap FIR filter $c_p(t)$. Finally the noise signal acquired in the pickup is filtered and subtracted from the FIDs signals of the field probes in order to suppress the power amplifier noise:

$$\tilde{s_p}(t) = s_p(t) - s_{pu}(t) \otimes c_p(t)$$

Experiments were performed on a 7T human whole body system (Philips Healthcare, Cleveland, Oh.). The signals from the ^{19}F field probes and the pick-up loop were acquired with a stand-alone field camera system[3] which simultaneously records the ^{19}F and the ^{1}H band on each of its 16 channels. The field probes were equipped with gradient switching compatible RF shields and notch filters adjusting the dynamic range of the proton and the fluorine band to similar levels (Fig. 1).

Results: Fig. 2. a) shows the FIDs acquired with strongly increased noise floor during a 10 ms block pulse at the beginning. The relative weights between the probes and the pickup and the resulting filters are plotted in b) and c). As d) shows, the noise could be supressed by 6 dB and more in most channels. Fig. 2 e)-k) shows the recording of the full sequence (RF, B_0, gradients and excitation k-space trajectory) of a pencil-beam navigator pulse with noise subtraction (blue) and without (red) for 20 interleaves plotted on top of each other. As seen, the increased noise level of the FID propagates into the measured fields and can even cause critical wrapping errors if not subtracted. These wrapping errors lead to large errors and inconsistencies in the k-space trajectory as seen by the high variance between the red k-space trajectories among different interleaves not present in the blue curves.

Discussion: The achieved noise suppression allows monitoring the magnetic field with sufficiently high sensitivity and accuracy even during high power transmission pulses without requiring any adaptations of the MR scanner. This is of particular use to study excitation profiles concurrently with the pulse or for obtaining very accurate information about the imaging signal phase evolution which is typically referenced to the magnetic centre of the excitation pulse previously not assessable to the monitoring. Further, gradient and higher order field evolutions can be acquired along with RF pulses with highly stringent relative timing. Thereby the full information about the sequence is obtained as it is performed by the native scanner without any modifications potentially introducing delays, shifts or drifts.
The remnant additional noise during the RF pulse was found to be not correlated with the signal in the pick-up loop. Therefore it is believed that they stem from different sources. These sources are presumably based on non-linear behaviours of the involved components carrying high RF currents and can be further reduced by capturing them with more dedicated pick-ups as experimentally confirmed.

References: 1)Barmet, MRM 2008 2) Duerst MRM 2014
3) Dietrich ISMRM 2012