Fast Reconstruction for RF Monitored Sweep Imaging with Sideband Excitation

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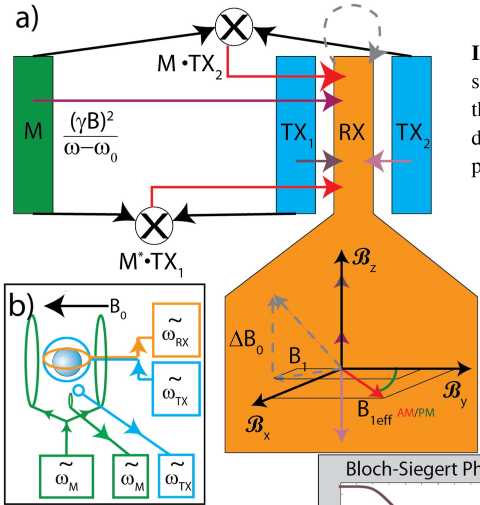
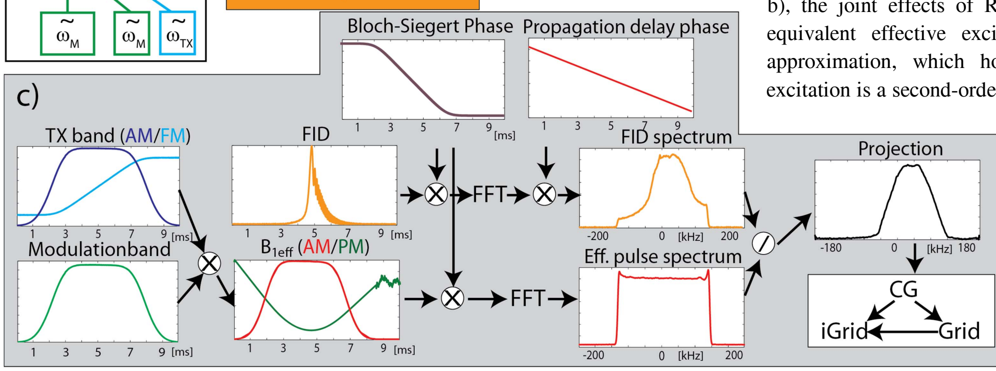
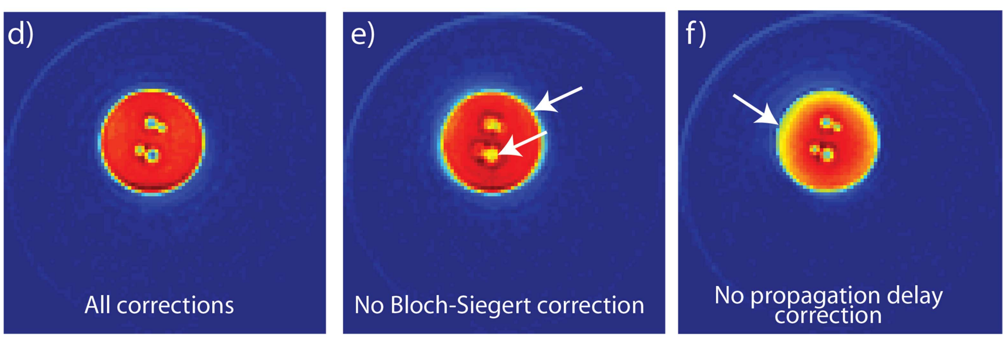


Introduction: Pulsed NMR spectroscopy and imaging using stochastic[1] or swept[2] excitation with concurrent signal acquisition is of particular use for samples exhibiting very short T_2 relaxation times. In these techniques, the received signal is strongly modulated by the excitation pulse and is traditionally first deconvolved to disentangle the NMR spectrum from that of the pulse. Alternatively, an algebraic approach has recently been proposed[3], which offers more freedom in incorporating details of pulse shape and data sampling. The requirements on the fidelity and stability of the excitation pulse are extremely high and hence it has been proposed to monitor the pulse concurrently with the experiment by pick-up coils[4]. In the same work, the additional use of sideband modulation has been suggested for truly concurrent excitation and detection[4]. The present work targets the resulting image reconstruction problem. With common algebraic treatment, accounting for monitored RF waveforms results in excessive computational effort since it poses a separate large linear problem for every projection in a 3D scheme. Instead we propose a substantially faster Fourier reconstruction approach for concurrently excited and RF-monitored sequences, incorporating the required correction terms in a computationally efficient way.

Methods: The deconvolution step is applied to individual profiles. In the case of sideband excitation (Fig. b), the joint effects of RF transmission and B_0 modulation translates into equivalent effective excitation in the rotating spin frame. To a good approximation, which holds for most practical power levels, sideband excitation is a second-order effect. Hence the effective B_1 in the rotating frame is given by the product of the complex waveforms at the modulation and the sideband frequencies (Fig. a, red arrow). Additionally, the Bloch-Siegert shift induced by off-resonance RF transmission, equally a second-order effect, is taken into account (Fig. a, purple and violet arrows). Finally, a propagation delay difference between the NMR and the RF monitoring signal path can occur. This is particularly the case in a sideband setup as very narrowband filters are involved. The net algorithm is depicted in Fig. c. First the received RF waveforms are multiplied to form the effective pulse. Depending on which sideband is excited, complex conjugation is applied to the modulation signal. Since the Bloch-Siegert shift is equivalent to a shift in $f_0(t)$, a correction phase $p(t) \propto \int_0^t (B_{TX}(t'))^2 dt'$ is applied before the FFT of both, the FID and the effective pulse. The propagation delay is corrected by applying a phase gradient to the FID spectrum and finally deconvolution is achieved by frequency-wise division of the corrected FID and pulse spectrum. The Bloch-Siegert shift is measured in-situ while the propagation delay can be obtained on the bench by a network analyzer transmission measurement. The resulting 1D radial projections are then gridded into Cartesian 3D k-space and a few steps of conjugate-gradient iteration are used to complete density correction[5].





Results: Figures d) to f) show images reconstructed with and without the proposed corrections for 3D sweep imaging of a grape with sideband excitation, fully concurrent data acquisition as well as RF monitoring (Philips Achieva 7T, 10mT/m gradient, 96^3 matrix, 7 cm FOV. The fully corrected image is virtually artefact-free up to common ringing and exhibits uniform signal response across the flesh. Omitting Bloch-Siegert correction significantly blurs the image and lowers the contrast whereas not correcting for the propagation delay of 500 ns resulted in bell-like weighting of image intensities. The fully corrected 3D reconstruction took about 6 min using Matlab on a standard PC:

Discussion: Fast deconvolution based reconstruction of RF monitored sweep imaging- but also other correlation based sequences- offers the possibility to implement the most important corrections numerically efficiently. The RF monitoring allows reducing the very high demands on the timing, linearity and fidelity imposed to the transmit chain and increases the robustness of the sequences even in presence of changes in the system e.g. induced by heating of components or load changes in the coil. The presented approach cannot only be applied to experiments applying sideband excitation, but also data acquired from gapped transmission or concurrent excitation can be reconstructed using RF monitoring and the presented algorithm. The Bloch-Siegert term is of course only of significance in the case of sideband excitation or when other off-resonant RF irradiation is applied, however any spatially uniform temporal variation of the resonance frequency, e.g. B_0 induced, can be corrected in the mentioned way.

References: 1) Bluemich, Enc Magn Reson 2007, 2) Idiyatullin et al. J Magn Reson 2008 3) Weiger et al. Magn Reson Med 2010, 4) Brunner et al. ISMRM 2012 5) Pruessmann et al Magn Reson Med 2001