RF Frequency Encoding Using the Bloch-Siegert Shift

Sai Abitha Srinivas[1,2], Mark A. Griswold[3], and William A. Grissom[2]

[1]Biomedical Engineering, Vanderbilt University, Nashville, TN, United States, [2]Biomedical Engineering, Case Western Reserve University, Cleveland, OH, United States, [3]Radiology, Case Western Reserve University, Cleveland, OH, United States

Introduction and Motivation

Conventional MRI gradients have several drawbacks. Alternative spatial encoding methods have been proposed that use RF gradients[1-3] instead of B_0 gradients for phase and slice encoding. However, frequency encoding is the fastest encoding mechanism in MRIs but has never been demonstrated experimentally before using RF gradients. This is due the requirement of being able to simultaneously transmit and receive (STAR) signals without overwhelming the receiver, and because all previous RF encoding methods required the magnetization to leave the transverse plane to accrue spatially-dependent phases.

This work describes the first system and images that implement RF frequency encoding using the Bloch Siegert (BS) shift[4-6]. We developed: 1.) An **injection transformer** method to enable simultaneous transmission of an off-resonant RF pulse during signal recording. 2.) A suitable RF coil for transmission of BS pulses and a pulse sequence design. 3.) A process to remove residual leaked transmit signal, yielding a clean frequency encoded proton signal. Overall, the scan was validated in a structured phantom on a **47.5mT open low field scanner**.

STAR Hardware

A toroidal injection transformer with two primary and one secondary windings (12 tri-windings, carbonyl iron core) was used to actively cancel the signal induced in the receive coil by the encoding pulse, before it reached the spectrometer.

- First primary winding → MR signal from the imaging Rx coil + leakage signal from the transmit coil that the imaging Rx coil sees.
- Second primary winding → cancellation signal possessing the same magnitude as the encoding signal but with an opposite phase.
- Secondary winding then exclusively carries the NMR signal.

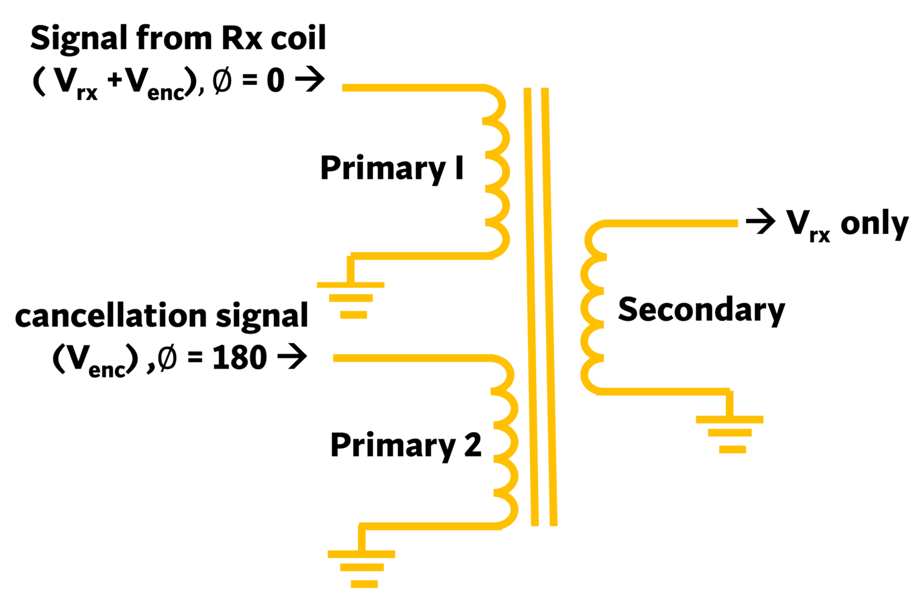

Fig 1: Illustration of cancellation using an injection transformer setup where V_{rx} is the MR signal and V_{enc} is the leakage signal.

Pulse Sequence and Reconstruction

A 2D GRE pulse sequence as shown in Fig 5 was used. A swept AM and FM BS encoding pulse applied pre-phasing (10ms) and a flat AM and FM pulse applied readout frequency encoding (21.48ms), with opposite FM polarity. BS offset = 10kHz was used for these pulses.

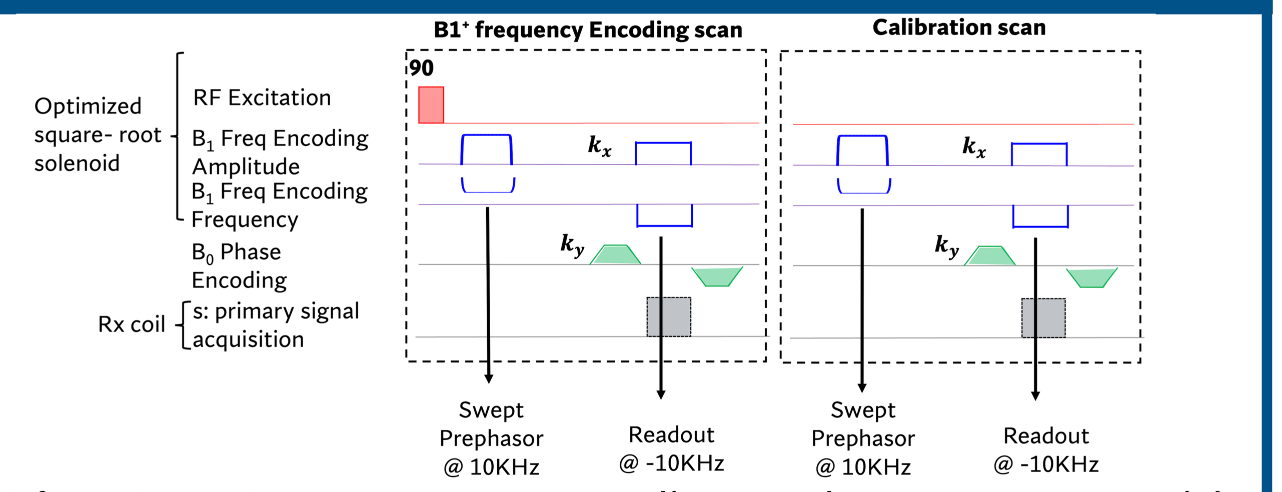

Fig 5: RF Frequency encoding pulse sequence with calibration for residual leakage signal removal

A Calibration scan without the imaging excitation pulse was added for every phase encode to enable subtraction of any residual leakage signal post processing. The maximum B_1 = 0.55G in ROI and thus, the B_{eff} tilt angle[6] was 0.25 rad causing negligible elliptical polarization[6]. Therefore, an **inverse iFFT reconstruction** is performed.

Experimental Hardware and Setup

- An optimized RF coil[7] was used for encoding with a square root field shape. A single loop coil was used as the imaging Rx coil to image a 2-ball phantom filled with mineral oil. Coils were >-60dB decoupled.

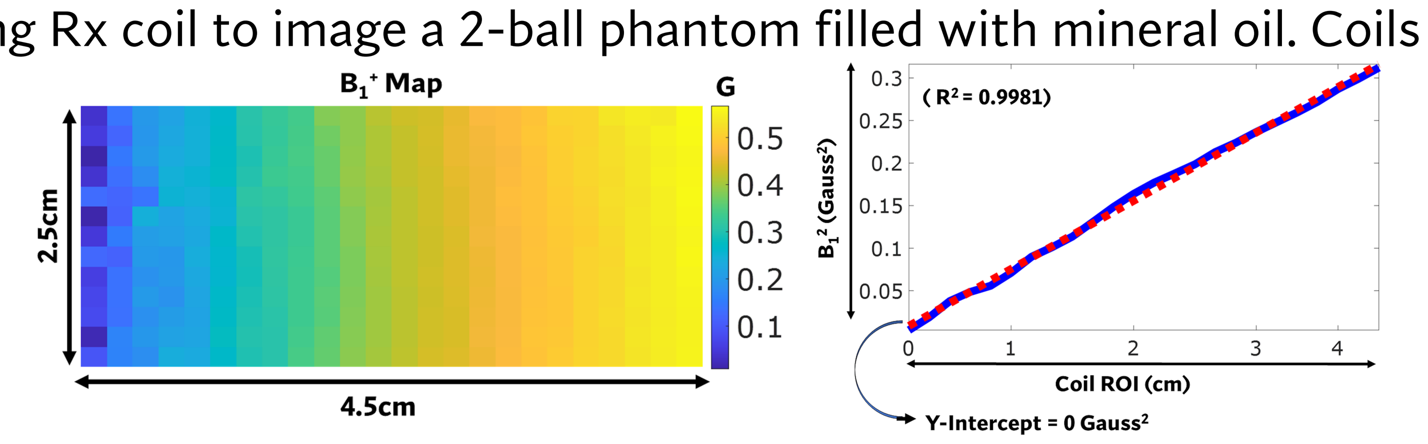

Fig 2: Left: B1+ Map of Tx coil. Right: mean B1+ squared field of the Tx coil

- A Tecmag redstone (Houston, TX, USA) spectrometer transmitted both encoding and cancellation signals.
- Cancellation signal was sent through a reed relay TR switch[8] with >60dB isolation → avoids power reflection from the STAR transformer.

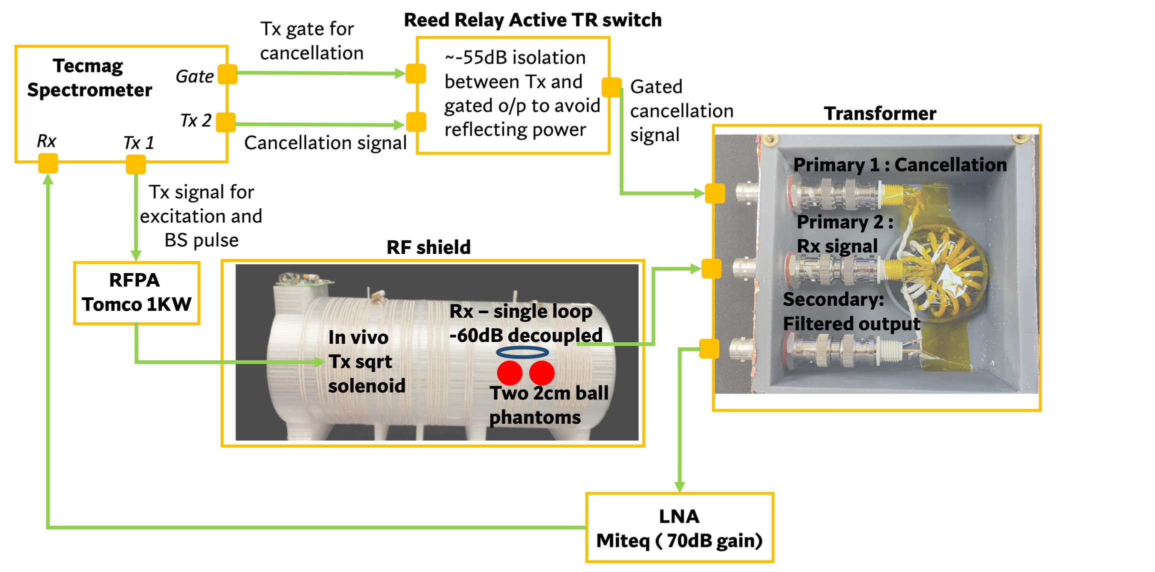

Fig 3: RF Frequency encoding setup in an open 47.5mT scanner

- Cancellation pulse was calibrated by adjusting both phase and amplitude to achieve maximum cancellation of leakage signal. BS Encoding pulse was pre-emphasized → avoids shaping of BS pulse → higher cancellation of leakage signal.

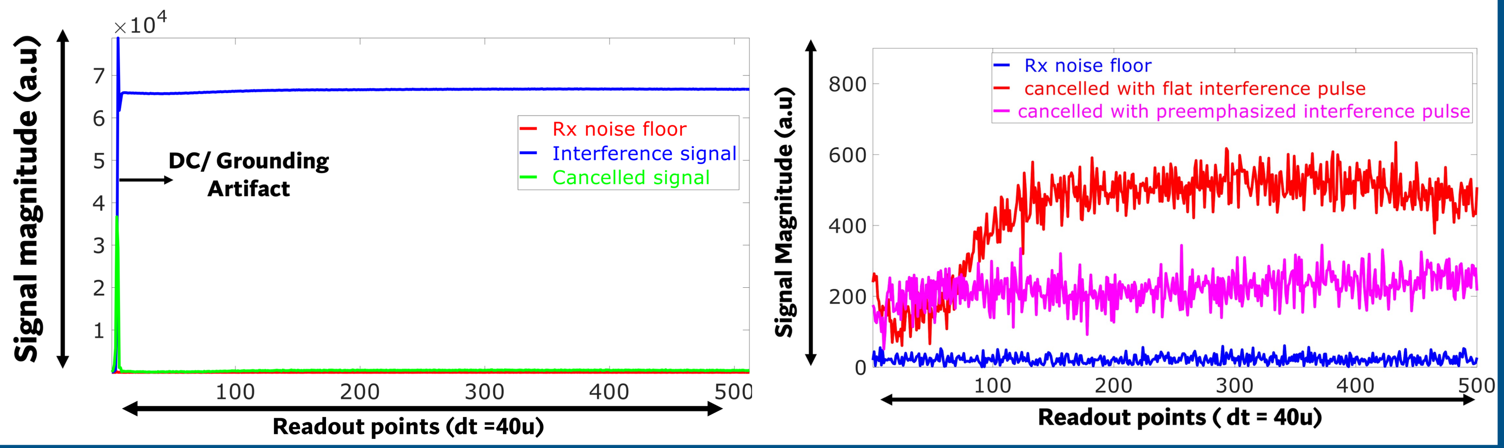

Fig 5: Left: Cancellation achieved using injection transformer with flat BS pulse, Right: Comparison of cancellation using pre-emphasized and flat BS pulses.

Results

The STAR injection transformer was measured to be 96.5% efficient via imaging tests due to use of a low-loss core and litz wire. No heating of core was observed after 3 hours of continuous use. A 99.75% cancellation was achieved using this transformer setup with a 13W encoding pulse. For this experiment (B_1 = 0.55G) 1.4232 G/m effective gradient field strength and a nominal resolution of 8mm was achieved.

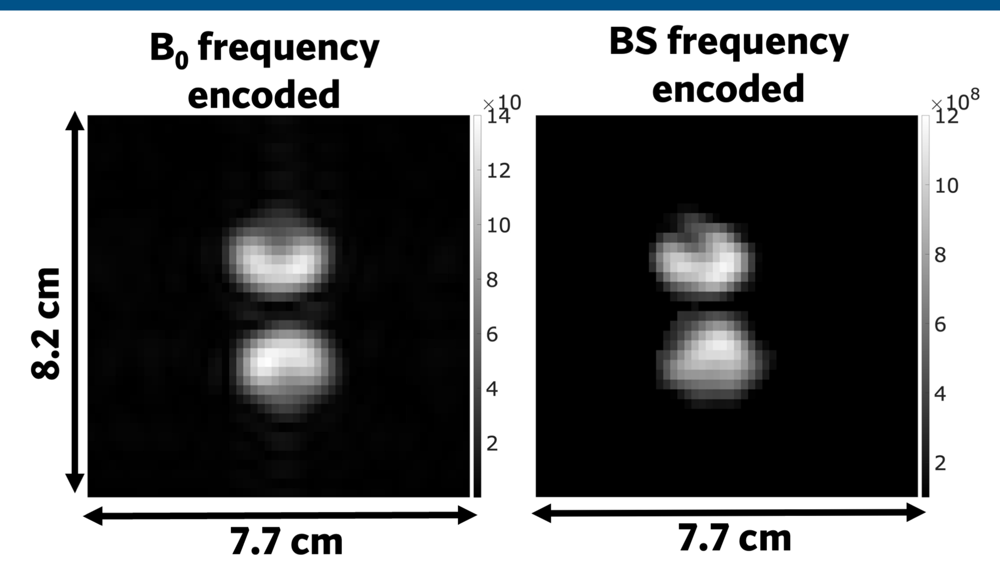

Fig 6: Left: B0 , Right: BS – Frequency encoded 2D images of 2-ball phantom

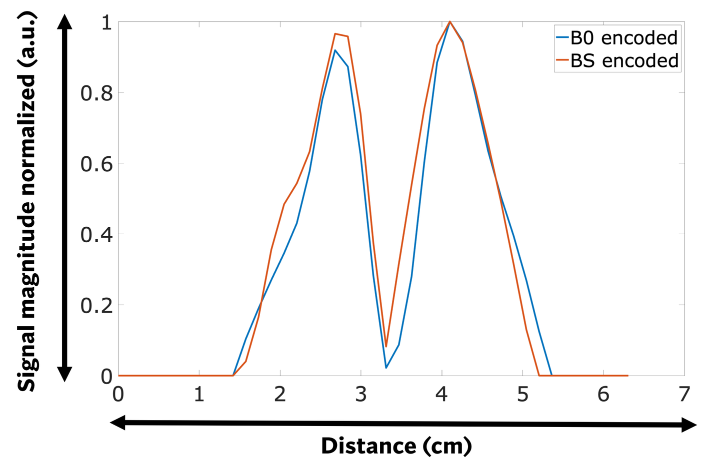

Fig 7: 1D profiles of B0 and BS frequency encoded scans

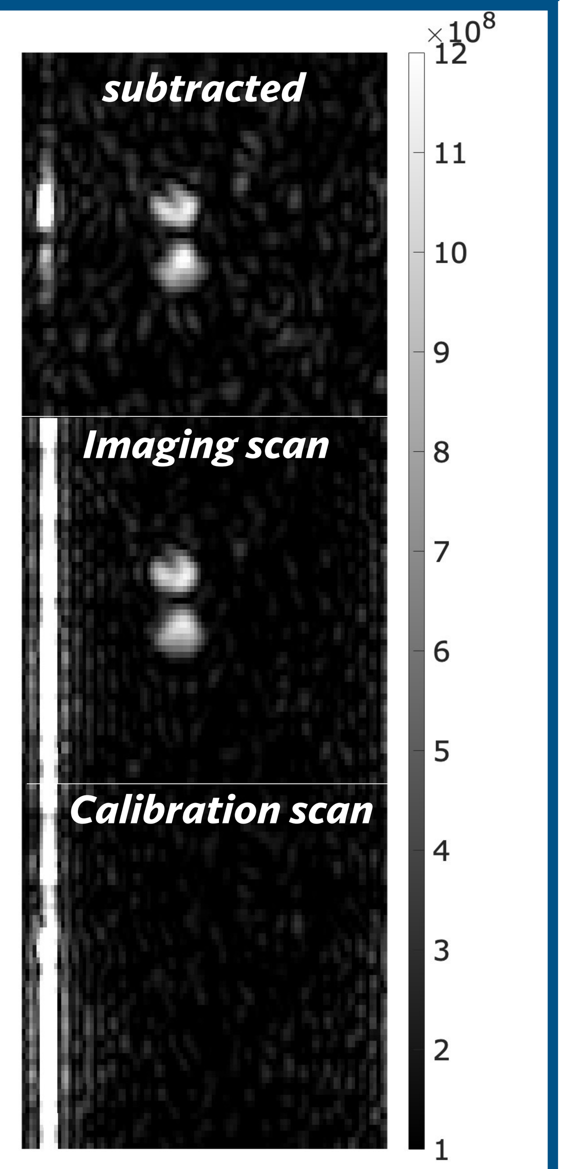

Fig 8: comparison of of imaging and calibration scans

Discussion and Future Work

We showed for the first time, a novel simultaneous transmit and receive filter using transformers which are easily translatable and costs <$30 to make. We also show that simple pulse sequences and reconstructions can be used to achieve RF frequency encoding. We compared the BS-encoded images to B_0-encoded images to validate the setup. While this is the first proof of principle study, further development involves techniques to improve resolution by optimizing hardware. Overall, we have for the first time ever demonstrated RF gradient-based Fourier frequency encoding experimentally.

References

[1] D. I. Hoult. J Magn Reson, 33(1):183–197, 1979. [2] J. C. Sharp and S. B. King. Magn Reson Med, 63(1):151–161, 2010. [3] Torres, E., Froelich et.al. *Magn reson Med*, 87(2):674–685, 2022. [4] Bloch, F. and Siegert, A. *Physical l Review*, 57(6):522. 1940. [5] W. A. Grissom, Z. Cao, and M. D. Does. J Magn Reson, 242:189–196, 2014. [6] Cao FE [7] Srinivas SA et.al. ISMRM, p 1589, 2023. [8] Straney, D., Cooley, C. Z., and Rosen, M. S. *ISMRM*, p 1395, 2022.

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