# Fast and Robust $B_1$ Mapping at 7T by the Bloch-Siegert Method

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**Introduction:** $B_1^+$ mapping has a variety of applications including the design of RF pulses in parallel transmit systems, and flip angle calibration for $T_1$ mapping. Many existing $B_1^+$ mapping methods suffer from $T_1$ dependence, long scan time or inability to handle the large $B_1^+$ inhomogeneity that occurs even across the human brain at 7T. The Bloch-Siegert $B_1^+$ mapping method has been recently introduced [1], and shown to be independent of TR, $T_1$ relaxation, flip angle, chemical shift, background field inhomogeneity, and magnetization transfer, thereby promising accurate and efficient $B_1^+$ mapping. To date, BS $B_1^+$ mapping has only been applied at 3T, which motivated us to implement and evaluate the method at 7T.

**Theory:** We first summarize the basic principles of the BS $B_1^+$ mapping method, with reference to Fig. 1 and Eqs. 1-3. An off resonance RF pulse (referred to as the BS pulse) with specific shape, duration, peak amplitude $B_{1,peak}$ set equal to the peak amplitude of the excitation pulse, and constant resonance offset $\Delta\omega_{BS}$, is applied immediately following a conventional slice- or slab-selective RF excitation pulse, with subsequent spatial encoding and signal readout using a conventional gradient echo sequence (GRE). This BS pulse induces a transverse magnetization phase $\varphi_{BS}$ which depends on the $B_{1,peak}$ amplitude, according to Bloch-Siegert theory [2] (Eq. 1). A key feature of this method is the use of phase difference imaging, or what we term "differential mode" BS $|B_1^+|$ mapping, involving the sequential application of positive and negative resonance offset BS pulses with subsequent formation of the phase difference image, which effectively isolates the $|B_1^+|^2$-dependent phase from all other sources of image phase. We introduce here an extension to the originally described method, involving the formation of the phase sum image, or what we term "common mode" BS $\angle B_1^+$ mapping, which produces an image in which the BS-induced $|B_1^+|^2$-dependent phase has been cancelled, and all other sources of image phase are displayed. If a previously acquired $B_0$ map is acquired, we can then compute and subtract the $B_0$-dependent phase, leaving behind a pure $\angle B_1^+$ dependence. In this way, using both differential and common modes, we obtain $B_1^+$ magnitude and phase images from a single scan.

**Methods:** In vivo volunteer experiments were performed on a whole-body 7T system (GE Healthcare, Waukesha, WI), equipped with 2-ch parallel transmit hardware, using a 2-ch T/R birdcage head coil (Nova Medical Inc., Wilmington MA). To maximize BS $|B_1^+|$ map SNR, Eq. (1) shows that we should minimize $\Delta\omega_{BS}$ subject to minimal direct saturation of the water peak, while maximizing $B_{1,peak}$, subject to SAR constraints. An 8 ms Fermi-shaped BS pulse was selected, and a resonance offset of 4 kHz was chosen [1], yielding a calibration constant $K_{BS}$ of 74.02 radians/guass$^2$. The sequence was run twice, with resonance offset frequencies set to +4 kHz and –4 kHz, respectively. Other sequence parameters were: minimum TE=11.6 ms to maximize SNR, TR=150 ms to stay well within SAR guidelines, FOV=24 cm, acquisition matrix of 64*64 and 5 mm slice thickness. We repeated this for each channel on the 2-channel system and generated the corresponding $B_1^+$ maps. The total scan time was 13 s for acquisition of the $B_1^+$ map from each channel. We also acquired the $B_1^+$ maps of the same slice using the double angle (DA) method; in this case imaging parameters were matched to the BS sequence with the exception of the following: TR=5 s, TE=5 ms, flip angles 60° and 120°, total scan time 640 s. The BS $B_1^+$ maps were then provided as input to an optimization algorithm to find the best amplitude and phase of channel 2 versus channel 1 to obtain the best transmitted $B_1^+$ uniformity [3].

**Results:** Fig. 2 shows resulting $|B_1^+|$ maps in the central axial plane through the brain of a healthy adult volunteer (a,b: I channel, c,d: Q channel), with BS maps shown in the left column compared with DA maps in the right column. The BS maps have good SNR and are comparable the DA maps, despite the 50-fold reduction in scan time. The relative phase maps (difference in $\angle B_1^+$ between I and Q channels) obtained using BS common mode and DA methods are shown in Fig. 3 (a) and (b), respectively. Fig. 3 (c) shows the difference between BS and DA phase maps, which is then re-displayed after intensity scale magnification by a factor of 10 in (d). These lower two images show that BS $\angle B_1^+$ maps have high SNR and match DA $\angle B_1^+$ maps to within approximately 10%.

(1) $$\varphi_{BS} = \int_0^T \frac{\gamma^2 B_1^+(t)^2}{2\Delta\omega_{BS}} = K_{BS} \times (B_{1,peak}^+)^2$$

(2) $$|B_1| = \sqrt{(\varphi_{BS,+4kHz} - \varphi_{BS,-4kHz})/(2K_{BS})}$$

(3) $$\angle B_1 = (\varphi_{BS,+4kHz} + \varphi_{BS,-4kHz})/2$$

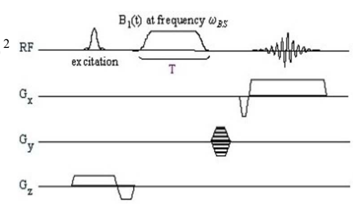


Fig 1: GRE seq. with added BS pulse

**Discussion:** The Bloch-Siegert method for $B_1^+$ mapping has been shown to be fast, accurate and robust i.e. insensitive to T1, TR and $B_0$ inhomogeneities [1]. Here, we have shown that for high field (7T) application of the BS method, the only limitation is SAR, which will limit the minimum TR achievable. The SNR of the $|B_1^+|$ maps is dependent on the BS pulse amplitude, off-resonance frequency and period as well as the SNR of the underlying GRE image. The amplitude and period of the BS pulse is limited by hardware limitations and SAR. The off-resonance BS pulse has to be designed to minimize direct saturation of the water peak. By running the sequence at both +4 kHz and –4 kHz off resonance frequencies we were able to 1) eliminate $B_0$ inhomogeneity and chemical shift effects, 2) generate both $B_1^+$ amplitude and phase at the same time and finally 3) increase the SNR of the final $B_1^+$ map. These characteristics make the Bloch-Siegert method a promising candidate for high field $B_1^+$ mapping applications.

**References:** **[1]** Sacolick L, et al, Magn Reson Aug 2009, In Press, **[2]** Ramsey NF. Phys Rev 1955;100:1191-1194, **[3]** K. Setsompop, et al, MRM, 59(4): 908–915, 2008. **Ack:** GE Healthcare research support.

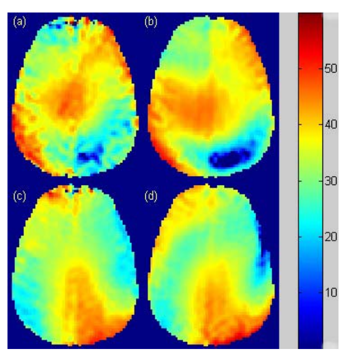


Fig 2: Comparison of BS (a & c) and DA (b & d) B1 maps

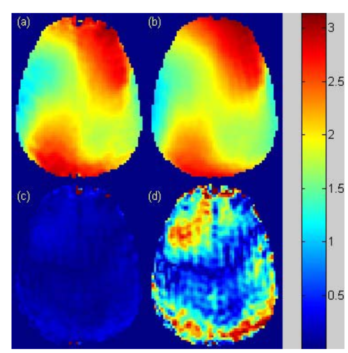


Fig 3: Relative phase between I and Q by (a) BS and (b) DA methods. (c) is the difference between (a) and (b) which is magnified by 10 in (d)