FULL PAPER

Investigation of the influence of B₀ drift on the performance of the PLANET method and an algorithm for drift correction

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Purpose: The PLANET method was designed to simultaneously reconstruct maps of T₁ and T₂, the off-resonance, the RF phase, and the banding free signal magnitude. The method requires a stationary B₀ field over the course of a phase-cycled balanced SSFP acquisition. In this work we investigated the influence of B₀ drift on the performance of the PLANET method for single-component and two-component signal models, and we propose a strategy for drift correction.

Methods: The complex phase-cycled balanced SSFP signal was modeled with and without frequency drift. The behavior of the signal influenced by drift was mathematically interpreted as a sum of drift-dependent displacement of the data points along an ellipse and drift-dependent rotation around the origin. The influence of drift on parameter estimates was investigated experimentally on a phantom and on the brain of healthy volunteers and was verified by numerical simulations. A drift correction algorithm was proposed and tested on a phantom and in vivo.

Results: Drift can be assumed to be linear over the typical duration of a PLANET acquisition. In a phantom (a single-component signal model), drift induced errors of 4% and 8% in the estimated T₁ and T₂ values. In the brain, where multiple components are present, drift only had a minor effect. For both single-component and two-component signal models, drift-induced errors were successfully corrected by applying the proposed drift correction algorithm.

Conclusion: We have demonstrated theoretically and experimentally the sensitivity of the PLANET method to B₀ drift and have proposed a drift correction method.

KEYWORDS
B₀ drift, PLANET, quantitative MRI, relaxometry

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1 | INTRODUCTION

Quantitative MRI is used widely to obtain quantitative characteristics of tissues related to their biological and physiological properties, based on which tissues can be differentiated and associated with specific diseases. The measurement of the relaxation times of tissues (or quantitative relaxometry) is particularly important for clinical applications in oncology and regenerative medicine.\(^1\) Many different techniques exist for quantitative relaxometry, such as standard inversion recovery and multiecho spin-echo-based approaches,\(^2,4\) many rapid SSFP approaches like inversion-recovery TrueFISP,\(^5,6\) the variable flip angle approach or DESPOT-1 and DESPOT-2,\(^7,9\) the triple-echo steady-state approach,\(^10\) the triple-echo balanced SSFP (bSSFP) data.\(^12\) The method is based on linear least-squares fitting of an ellipse to phase-cycled bSSFP data in the complex signal plane and subsequent analytical parameter estimation from the fitting results.

We recently introduced a method called PLANET to simultaneously reconstruct maps of the relaxation times \(T_1\) and \(T_2\), the local off-resonance \(\Delta f_0\), the RF phase, and the banding free signal magnitude, using phase-cycled balanced SSFP (bSSFP) data.\(^12\) The method is based on linear least-squares fitting of an ellipse to phase-cycled bSSFP data in the complex signal plane and subsequent analytical parameter estimation from the fitting results.

A bSSFP signal is strongly dependent on local resonant frequency, and the use of RF phase cycling shifts the off-resonance profile of the signal dependent on the RF phase increment. The main requirement of the PLANET model is a stationary main magnetic field \((B_0)\) over the course of the acquisition, which usually consists of 8-10 dynamics and takes around 10 minutes for full brain coverage with FOV of \(220 \times 220 \times 100 \text{ mm}^3\) and voxel size of \(1 \times 1 \times 4 \text{ mm}^3\) (without any acceleration technique). In this case, accurate and precise parameter estimation can be achieved for a single-component voxel, as we showed in a previous study,\(^13\) whereas systematic errors in parameter estimates are expected when multiple signal components with different relaxation times and frequencies are present within a voxel.\(^13\)

Due to intensive gradient activity, the requirement of a stationary \(B_0\) field can be difficult to meet, and as a result, \(B_0\) drift can occur, which might result in errors in the estimated parameters. The severity of drift effect depends on the field strength, history of gradient activity and heating of metallic components of the scanner, the acquisition time, the used gradient mode, shimming, and more, which vary among different systems and over time.

The purpose of this work was to investigate the effects of \(B_0\) drift and to assess the influence of drift on the quantitative parameters estimated using the PLANET method. We first derived a geometrical interpretation of the influence of drift on a single-component phase-cycled bSSFP signal based on a mathematical model. Subsequently, based on this geometrical interpretation, we developed a strategy for drift correction. Next, we experimentally showed the influence of drift on the parameter estimates for a single-component model in a phantom and for a 2-component model of white matter (WM) in the human brain. We assessed the effects of drift for both single-component and two-component signal models and evaluated the performance of the drift correction algorithm in both cases by looking at drift-induced errors in the quantitative parameter estimates. Finally, we performed numerical simulations for both single-component and two-component signal models to verify the experimental results.

2 | METHODS

2.1 | How drift influences a single-component phase-cycled bSSFP signal

For a single-component model with monoexponential transverse and longitudinal relaxation, the complex phase-cycled bSSFP signal can be represented as an ellipse in the complex plane\(^14,15\) as follows:

\[
I = M_{\text{eff}} \frac{1 - a e^{(\theta_0 - \Delta \theta)}}{1 - b \cos(\theta_0 - \Delta \theta)} e^{i \varphi},
\]

where \(M_{\text{eff}}, a,\) and \(b\) are parametric functions of \(T_1, T_2,\) TR, and flip angle (FA); \(\Delta \theta\) is the user-controlled RF phase increment (rad); \(\varphi = 2\pi (\delta_{\text{CS}} + \Delta f_0) TE + \phi_{\text{RF}}\) is the rotation angle of the ellipse around the origin with respect to its vertical form\(^14\); \(\theta_0 = 2\pi (\delta_{\text{CS}} + \Delta f_0) TR;\) \(\Delta f_0\) is the local off-resonance (Hz); \(\phi_{\text{RF}}\) is the combined RF transmit and receive phase; and \(\delta_{\text{CS}}\) is the chemical shift of the species (Hz) with respect to the water peak.

After substitution, Equation 1 can be rewritten as

\[
I = M_{\text{eff}} \frac{1 - a e^{(2\pi (\delta_{\text{CS}} + \Delta f_0) TR - \Delta \theta)}}{1 - b \cos(2\pi (\delta_{\text{CS}} + \Delta f_0) TR - \Delta \theta)} e^{(2\pi (\delta_{\text{CS}} + \Delta f_0) TE + \phi_{\text{RF}})}. \tag{2}
\]

A graphical representation of the ellipse described by this equation in the complex plane is shown in Figure 1A.

The frequency drift is modeled as \(\Delta f_0 \rightarrow \Delta f_0 + \Delta f_{\text{drift}}(t)\), where \(\Delta f_{\text{drift}}(t)\) is the time-dependent frequency drift during PLANET acquisition and is equal to \(\gamma \Delta B_0(t)\), where \(\gamma\) is the gyromagnetic ratio equal to 42.58 MHz/T. Then Equation 2 becomes

\[
I = M_{\text{eff}} \frac{1 - a e^{(2\pi (\delta_{\text{CS}} + \Delta f_0) TR - \Delta \theta + 2\pi TR \Delta f_{\text{drift}}(t))}}{1 - b \cos(2\pi (\delta_{\text{CS}} + \Delta f_0) TR - \Delta \theta + 2\pi TR \Delta f_{\text{drift}}(t))} e^{(2\pi (\delta_{\text{CS}} + \Delta f_0) TE + \phi_{\text{RF}} + 2\pi TE \Delta f_{\text{drift}}(t))}. \tag{3}
\]
The first part of Equation 3 multiplied by the first exponential represents the elliptical equation in Equation 2, but with a modified time-dependent RF phase-increment scheme: \[ \Delta \theta_{\text{new}}(t) = \Delta \theta - 2\pi TR \Delta f_{\text{drift}}(t) \]. This corresponds to a drift-dependent displacement of all data points along the ellipse as illustrated in Figure 1B. Note that if only this effect of drift is taken into account, the data points remain on the “nondrifted” ellipse (i.e., the ellipse fitted to the data points not influenced by drift).

There is, however, another effect of the drift, caused by the last exponential factor in Equation 3. Using this factor, drift leads to an additional rotation of the data points around the origin, as illustrated in Figure 1C,D. As drift is time-dependent, the rotation angle differs per data point.

These 2 effects together relocate the data points in the complex plane away from the nondrifted ellipse and result in a nonelliptical distribution of the points. Ignoring the effects of B₀ drift, fitting an ellipse to the drifted data points (i.e., data points relocated by drift from their nondrifted positions) would lead to different fit results compared with the fit for the nondrifted case (Figure 1E). After performing PLANET postprocessing,¹² this would result in errors in the parameter estimates.

We propose a drift correction method that aims to relocate each data point back to the position in the complex plane that it would have in the case without drift.

### 2.2 | Drift correction method

Based on this analysis, we propose a 3-step drift correction algorithm:

1. Calculation of the spatio-temporal B₀ drift during the phase-cycled PLANET acquisition \( \Delta f_{\text{drift}}(i, j)(t) \), where \( n \) is the number of the dynamic acquisition, \( t \) is the time, and \( (i, j) \) are the spatial indices of the voxel. One phase-cycled PLANET acquisition consists of \( N \) acquisitions. Assuming temporally linear drift over the duration of the phase-cycled PLANET acquisition, the frequency drift over the \( n \)th phase-cycled acquisition is estimated by

\[
\Delta f_{\text{drift},n}(i, j)(t) = n * \frac{\Delta f_{\text{total drift}}(i, j) \text{ (Hz)}}{N}, n = \{1, \ldots N\}, \quad (4)
\]

where the total drift over the phase-cycled PLANET acquisition \( \Delta f_{\text{total drift}}(i, j) \) is calculated by subtracting...
2 reference B₀ maps acquired right before and right after PLANET acquisition, and \( t = n \Delta t \) is the time point within the PLANET acquisition scheme corresponding to \( n \)th dynamic acquisition, where the dynamic acquisitions in the phase-cycled acquisition each have a duration \( \Delta t \).

2. Correction of \( M_{\text{diff}} \), \( T₁ \), and \( T₂ \) by multiplying the experimental complex data by \( e^{−i2πTRΔ\theta_n(i,j)(t)} \), the geometrical equivalent of which is the rotation of each drifted data point around the origin back to the nondrifted ellipse.

3. Correction of \( \Delta f₀ \) and \( \varphi_{\text{RF}} \) by defining \( \Delta \theta_{\text{new}}(i,j)(t) = \Delta \theta_n - 2πTRΔf_{\text{drift},n}(i,j)(t) \), which geometrically moves the drifted data points along the ellipse back to their nondrifted positions, where \( \Delta \theta_n \) is the user-controlled RF phase increment \( \Delta \theta_n = (n - 1) \cdot \frac{2π}{N} - π \), \( n = \{1, 2…N\} \), covering a full cycle of \( 2π \).

### 2.3 Temporal drift model

As we observed experimentally, B₀ drift on a long-time scale can be represented by an exponential function. In the proposed drift correction algorithm, we assumed the temporal evolution of the drift to be linear over the duration of 1 PLANET acquisition.

Here we compared 2 temporal drift models:

- A linear model described by Equation 4; and
- An exponential model described by

\[
\Delta f_{\text{drift},n}(i,j)(t) = A_{\text{drift}}(i,j) \left( 1 - \exp \left( - \frac{t}{b_{\text{drift}}(i,j)} \right) \right) . \tag{5}
\]

where \( \Delta f_{\text{drift},n}(i,j)(t) \) is the frequency drift over time \( t \), \( A_{\text{drift}} \) and \( b_{\text{drift}} \) are parameters describing the global spatial drift characteristics, and \( (i,j) \) are the spatial indices of the voxel.

### 2.4 Accuracy and precision in the estimated parameters and drift correction performance

The accuracy of the method was assessed by calculating relative errors \( (\varepsilon) \) in \( T₁, T₂, \Delta f₀, \) and \( \varphi_{\text{RF}} \) estimates before and after drift correction, as follows:

\[
\varepsilon_X = \frac{\bar{X} - X_{\text{true}}}{X_{\text{true}}} \cdot 100\% , \varepsilon_{X_{\text{cor}}} = \frac{\bar{X}_{\text{cor}} - X_{\text{true}}}{X_{\text{true}}} \cdot 100\% . \tag{6}
\]

The precision of the method was assessed by calculating the relative SD of \( T₁, T₂, \Delta f₀, \) and \( \varphi_{\text{RF}} \) estimates before and after drift correction, as follows:

\[
SD_X = \sqrt{\frac{1}{Z} \sum_{i=1}^{Z} (X^{i} - \bar{X})^2} \cdot 100\% , \tag{7}
\]

\[
SD_{X_{\text{cor}}} = \sqrt{\frac{1}{Z} \sum_{i=1}^{Z} (X_{\text{cor}}^{i} - \bar{X}_{\text{cor}})^2} \cdot 100\% ,
\]

where \( \bar{X} = \frac{1}{Z} \sum_{i=1}^{Z} X^{i} \) refers to the average of the values \( X^{i} \) affected by drift; \( X_{\text{cor}} = \frac{1}{Z} \sum_{i=1}^{Z} X_{\text{cor}}^{i} \) refers to the average of the values \( X_{\text{cor}}^{i} \) estimated after drift correction, assuming a true value of \( X_{\text{true}} \) for parameters \( T₁, T₂, \Delta f₀, \) and \( \varphi_{\text{RF}} \); \( i \) is an index for the voxels in a region of interest (ROI) (in experiments) or the current number of the simulation (in numerical simulations); and \( Z \) is the total number of voxels in an ROI (in experiments) or the total number of simulations (in numerical simulations).

To quantify the drift correction on \( T₁, T₂, \Delta f₀, \) and \( \varphi_{\text{RF}} \) estimates, \( \Delta_{\text{cor}} \) were determined as

\[
\Delta_{\text{cor}T₁} = T_{1\text{cor}} - T_{1\text{uncor}}, \quad \Delta_{\text{cor}T₂} = T_{2\text{cor}} - T_{2\text{uncor}},
\]

\[
\Delta_{\text{cor}f₀} = f_{0\text{cor}} - f_{0\text{uncor}}, \quad \Delta_{\text{corr}φ} = φ_{\text{RF cor}} - φ_{\text{RF uncor}}, \tag{8}
\]

\[
\Delta_{\text{cor}T₁}(\%) = \frac{T_{1\text{cor}} - T_{1\text{uncor}}}{T_{1\text{cor}}} \cdot 100\% , \quad \Delta_{\text{cor}T₂}(\%) = \frac{T_{2\text{cor}} - T_{2\text{uncor}}}{T_{2\text{cor}}} \cdot 100\% .
\]

### 2.5 Experiments

#### 2.5.1 Phantom experiments

To investigate the effects of drift on a single-component phase-cycled hSSFP signal model, and to test the drift correction algorithm, MRI experiments on a phantom (1.5-L plastic bottle filled with an aqueous solution of MnCl₂·4H₂O [concentration of approximately 55-60 mg/L]) were performed on a clinical 1.5T MR scanner (Ingenia; Philips, Best, Netherlands). A 15-channel head coil was used as a receiver. The experimental design is shown in Figure 2A.

To compare two temporal drift models, after the first reference B₀ mapping acquisition we repeated 5 times the PLANET acquisition. Each PLANET acquisition concerned.
For the PLANET acquisition with more severe drift, the $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps were reconstructed. Both linear and exponential temporal drift models were used to correct the drift over this PLANET acquisition; $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps were recalculated by applying the drift correction. Because $T_1$ estimates depend on FA (see Equation 10 in Shcherbakova12), a $B_1$ mapping sequence was acquired, and voxel-wise $B_1$ correction was performed while calculating the $T_1$ maps. The $B_1$ maps were calculated using a dual-TR actual FA imaging technique.16 The reference $T_1$ and $T_2$

**FIGURE 2** Experimental drift measurements in the phantom. A, Experimental design. B, Reference $B_0$ maps (obtained in 3D and shown only for 1 axial slice of the phantom). C, Calculated $B_0$ drift maps. D, Total drift map. E, Drift over 65-minute interval for 1 voxel in the center of the slice: Exponential temporal drift curve (red) fitted to the experimental data points (blue dots); lines connecting the experimental data points (blue). F, The example of original (measured) data points and drift-corrected data points with corresponding elliptical fits for 1 voxel in the middle of the slice. G, Example of original vertical ellipse and drift-corrected vertical ellipse for 1 voxel in the center of the slice.
**TABLE 1** Protocol parameter settings

### Phantom experiment at 1.5 T

| Parameter                  | Setting                                                                 |
|---------------------------|-------------------------------------------------------------------------|
| **PLANET: 3D phase-cycled bSSFP** |                                                                         |
| **FOV (m³)**             | 160 × 160 × 159                                                          |
| **Voxel size (mm³)**     | 1.1 × 1.1 × 3                                                            |
| **Acq. matrix**          | 144 × 145 × 53                                                           |
| **Rec. matrix**          | 160 × 160 × 53                                                           |
| **TR (ms)**              | 10                                                                      |
| **TE (ms)**              | 5                                                                       |
| **Flip angle**           | 30                                                                      |
| **Number of RF increment steps** | 10                                                                    |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Dummy pulses**         | 6 seconds for each dynamic                                              |
| **Total scan time (minutes)** | 13:46                                                                  |

| **Reference B₁ map (3D dual-TR SPGR)** |                             |
| **FOV (m³)**             | 160 × 160 × 159                                                          |
| **Voxel size (mm³)**     | 2.5 × 4 × 3                                                             |
| **Acq. matrix**          | 64 × 40 × 53                                                            |
| **Rec. matrix**          | 160 × 160 × 53                                                           |
| **TR (ms)**              | [30; 150]                                                               |
| **TE (ms)**              | 1.82                                                                   |
| **Flip angle**           | 60                                                                      |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Total scan time (minutes)** | 03:12                                                                  |

| **Reference off-resonance map (3D dual-echo SPGR)** |                             |
| **FOV (m³)**             | 160 × 160 × 159                                                          |
| **Voxel size (mm³)**     | 2.5 × 4 × 3                                                             |
| **Acq. matrix**          | 64 × 40 × 53                                                            |
| **Rec. matrix**          | 160 × 160 × 53                                                           |
| **TR (ms)**              | 30                                                                      |
| **TE (ms)**              | [4.6; 9.2]                                                              |
| **Flip angle**           | 60                                                                      |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Total scan time (minutes)** | 01:04                                                                  |

### In vivo experiments at 1.5 T and 3 T

| Parameter                  | Setting                                                                 |
|---------------------------|-------------------------------------------------------------------------|
| **PLANET: 3D phase-cycled bSSFP** |                                                                         |
| **FOV (m³)**             | 220 × 220 × 100                                                          |
| **Voxel size (mm³)**     | 0.98 × 0.98 × 4                                                          |
| **Acq. matrix**          | 220 × 220 × 25                                                           |
| **Rec. matrix**          | 224 × 224 × 25                                                           |
| **TR (ms)**              | 10                                                                      |
| **TE (ms)**              | 5                                                                       |
| **Flip angle**           | 20                                                                      |
| **Number of RF increment steps** | 10                                                                    |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Dummy pulses**         | 10 seconds for each dynamic                                             |
| **Total scan time (minutes)** | 11:00                                                                  |

| **Reference B₁ map (3D dual-TR SPGR)** |                             |
| **FOV (m³)**             | 220 × 220 × 100                                                          |
| **Voxel size (mm³)**     | 3.44 × 4 × 4                                                             |
| **Acq. matrix**          | 64 × 55 × 25                                                             |
| **Rec. matrix**          | 224 × 224 × 25                                                           |
| **TR (ms)**              | [30; 150]                                                               |
| **TE (ms)**              | 1.82                                                                   |
| **Flip angle**           | 60                                                                      |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Total scan time (minutes)** | 02:43                                                                  |

| **Reference off-resonance map (3D dual-echo SPGR)** |                             |
| **FOV (m³)**             | 220 × 220 × 100                                                          |
| **Voxel size (mm³)**     | 3.44 × 4 × 4                                                             |
| **Acq. matrix**          | 64 × 55 × 25                                                             |
| **Rec. matrix**          | 224 × 224 × 25                                                           |
| **TR (ms)**              | [30; 150]                                                               |
| **TE (ms)**              | 1.82                                                                   |
| **Flip angle**           | 60                                                                      |
| **NSA**                  | 1                                                                       |
| **Readout direction**    | AP                                                                      |
| **Total scan time (minutes)** | 02:43                                                                  |

(Continues)
values of the phantom were measured using a simultaneous spin-echo and inversion-recovery method (2D MIXED). Relevant protocol parameter settings are presented in Table 1.

The accuracy and precision in the parameter estimates, before and after linear drift correction, were assessed using Equations 6 and 7. Deviations quantifying the drift correction performed on $T_1$, $T_2$, $\Delta f_0$, and $\varphi_{RF}$ estimates were calculated using Equation 8. The ROI analysis was performed on the quantitative $T_1$ and $T_2$ maps calculated for the phantom: The ROI (approximately 2000 voxels) was placed in the center of the phantom on the selected slice.

### 2.5.2 | In vivo experiments

To investigate the effects of drift for a tissue in which multiple components are present, and to test the drift correction algorithm, experiments on the brain of healthy volunteers were performed on clinical 1.5T and 3T MR scanners. Both protocols included $B_1$ mapping acquisition, one PLANET acquisition in between two reference $B_0$ mapping acquisitions, and the reference $T_1$ and $T_2$ mapping acquisition with the protocol parameter settings given in Table 1.

A 2.5-ms-long RF excitation pulse was used in each PLANET acquisition to minimize magnetization transfer effects. Image registration (rigid) and Gibbs ringing filtering were applied to the brain data before performing the PLANET reconstruction. The $B_0$ drift maps were filtered (using a circular averaging filter with radius of 15) before applying the drift correction algorithm.

The $T_1$, $T_2$, $\Delta f_0$, and $\varphi_{RF}$ maps were calculated before and after drift correction. The $B_1$ correction was performed voxel-wise while calculating the $T_1$ maps. Deviations quantifying the drift correction performed on $T_1$, $T_2$, $\Delta f_0$, and $\varphi_{RF}$ estimates were calculated using Equation 8. The ROI analyses were performed on the quantitative $T_1$ and $T_2$ maps for both 1.5T and 3T data. The ROIs were manually delineated in WM on the selected slice in the area where the drift was the most pronounced (each ROI was approximately 100-150 voxels). The precision of the $T_1$ and $T_2$ measurements was evaluated by calculating SDs on $T_1$ and $T_2$ maps over the ROIs.

### 2.6 | Numerical simulations

#### 2.6.1 | Drift-induced errors and drift correction for a single-component signal model

To investigate the errors caused by $B_0$ drift for a single-component tissue model, numerical simulations were performed with relaxation times equal to those of the phantom material: $T_1 = 430$ ms and $T_2 = 50$ ms. The following parameter settings were used in the simulations: FA in the range of 0°-45°, TR in the range of 0-20 ms, 10 RF phase-increment values $\Delta \theta_n = \frac{\pi n}{10}$, $n = \{0, 1, ..., 9\}$, $M_{eff} = 10,000$, single peak with $\delta_{CS} = 0$, $\Delta f_0 = 5$ Hz,
and $\phi_{RF} = -0.2$ rad (these values were obtained experimentally in the phantom). The $B_0$ drift was assumed to be linear over time and spatially independent ($\Delta f_{\text{drift}} = [1 2 3 4 5 6 7 8 9 10]$ Hz), as we found in the experimental results in the phantom. Gaussian noise was added independently to the real and imaginary data, resulting in an SNR of about 230, which corresponds to the experimentally measured SNR in the phantom. The number of performed Monte Carlo simulations was 10,000.

The accuracy and precision in the $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ estimates were assessed using Equations 6 and 7.

### 2.6.2 Drift-induced errors and drift correction for a 2-component signal model

To investigate the errors in the parameter estimates caused by $B_0$ drift in the case in which two components are present in the signal, numerical simulations were performed for WM tissue at 3 T, which is known to be a two-component tissue.\(^\text{19,20}\)

Two single peaks were used in the simulations: the on-resonant dominant component and the smaller component with an average frequency shift of $\Delta f = 20$ Hz.\(^\text{20}\)

The dominant component has $T_{1D} = 1000$ ms and $T_{2D} = 80$ ms, with a volume fraction of 0.88; the smaller component has $T_{1S} = 400$ ms and $T_{2S} = 10$ ms, with a myelin water fraction of 0.12. The off-resonance $\Delta f_0 = 10$ Hz was used, and the RF phase offset $\phi_{RF} = -0.15$ rad was used. Gaussian noise was added independently to the real and imaginary data, resulting in an SNR ranging from 30 to 150. The number of performed Monte Carlo simulations was 10,000.

The simulations were performed using the complex phase-cycled bSSFP signal described by Equations 7 and 8 in our previous study\(^\text{13}\) for 3 cases:

- No $B_0$ drift;
- Linearly increasing over time and spatially independent frequency drift $\Delta f_{\text{drift}} = [1 2 3 4 5 6 7 8 9 10]$ Hz; and
- Linearly increasing over time and spatially independent frequency drift $\Delta f_{\text{drift}} = [1 2 3 4 5 6 7 8 9 10]$ Hz with sub-

The accuracy and precision in the $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ estimates were assessed using Equations 6 and 7, where the true parameter values were taken for the dominant WM component.

All simulations and calculations were performed in MATLAB R2015a (The MathWorks, Natick, MA).

### 3 RESULTS

#### 3.1 Experimental results in the phantom

Experimental results in the phantom are shown in Figure 2. Six reference $B_0$ maps acquired before and after each of 5 PLANET acquisitions and the corresponding calculated $B_0$ drift maps are presented in Figure 2B,C. A total drift of 28 Hz over a 65-minute scanning session was observed (Figure 2D).

The temporal drift was analyzed voxel-wise, and the example of the experimental data for 1 voxel (in the center of the phantom) is shown in Figure 2E. Over a 65-minute scanning time the temporal drift can be considered as an exponential function. Over the 11-minute duration of the PLANET acquisition, the drift with an average value of 10 Hz can be very well approximated with a linear function.

As an example, the initial data points and the data points after drift correction for 1 voxel are shown in Figure 2F, with corresponding elliptical fits. The conic vertical forms of these ellipses are shown in Figure 2G. The ellipses are different, as expected due to the drift.

The estimated $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps of the phantom before and after linear drift correction, as well as the reference $T_1$, $T_2$, and $\Delta f_0$ maps, are shown in Figure 3A-C. The drift correction was performed for the first PLANET acquisition, where the drift was more severe. The performance of linear and exponential drift correction was very similar; therefore, we did not include the maps of $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ after exponential drift correction in Figure 3. A reference RF phase map was not acquired and therefore is not shown. Deviations quantifying the amount of linear drift correction performed on all quantitative parameters are shown in Figure 3D,E. The drift correction decreased the $T_1$ values by about 4%, increased the $T_2$ values by about 8%, decreased the $\Delta f_0$ values by about 120%, and increased the $\phi_{RF}$ values by about 3%. The magnitude image with white vertical and horizontal lines used for $T_1$ and $T_2$ profiles, and $T_1$ and $T_2$ profiles on estimated, corrected, and reference maps, are shown in Figure 3F,G. The $T_2$ estimates are more sensitive to the drift than $T_1$ estimates.

The quantitative ROI analysis for parameters $T_1$, $T_2$, $\Delta f_0$, and the relative errors in these parameters before and after drift correction, are presented in Supporting Information Table S1. The $T_1$ values were overestimated due to drift by around 5% compared with the reference values, and the corrected $T_1$ values were in agreement with the reference values with an accuracy of 1%. The $T_2$ values were underestimated due to drift by about 10% compared with the reference values, and after drift correction they were in agreement with the reference values with an accuracy of 2%. The $\Delta f_0$ values estimated by means of PLANET were about 80% overestimated due to drift, and after drift correction they became similar to the reference $\Delta f_0$ acquired right before PLANET acquisition.

Despite the fact that there are no directly visible $B_0$ drift-related artifacts in quantitative parameter maps, there are $B_0$ drift-related errors in the quantitative $T_1$, $T_2$, and $\Delta f_0$ maps.

#### 3.2 Experimental results in the brain

##### 3.2.1 1.5 T

The results of the experiment in the brain of a healthy volunteer at 1.5 T are shown in Figure 4. The results are presented for 1 central slice. Spatially homogeneous drift was observed
**FIGURE 3** Experimental results in the phantom. A, Reference $T_1$, $T_2$, and $\Delta f_0$ maps. B, The $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps before drift correction. C, The $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps after linear drift correction. D, Maps of absolute $\Delta_{cor}$ quantifying the drift correction performed on $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$. E, Maps of relative $\Delta_{cor}$ quantifying the drift correction performed on $T_1$ and $T_2$. F, Magnitude image with white vertical and horizontal lines in the center of the slice, used for $T_1$ and $T_2$ profiles. G, The $T_1$ and $T_2$ profiles ($T_1$ and $T_2$ values representing single voxels along the selected lines on estimated, corrected, and reference maps). The values were averaged voxel-wise between the horizontal and vertical selected lines.
over 11-minute PLANET acquisition (Figure 4A) with an average value of 9 Hz. The $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps before and after linear drift correction are shown in Figure 4C,D. The banding-free magnitude and the reference $T_1$ and $T_2$ maps are shown in Figure 4B. Deviations quantifying the amount of linear drift correction performed on all parameters are shown in Figure 4E. The mean $T_1$ and $T_2$ values were calculated for WM. The results of the ROI analysis are given
TABLE 2  Quantitative results from the experiments in the brain at 1.5 T and 3 T: estimated, drift-corrected, and reference $T_1$ and $T_2$ values in white matter

| 1.5 T | Estimated values | Drift-corrected values | Reference values | Literature-published values$^a$ |
|-------|------------------|------------------------|-----------------|-------------------------------|
|       | $T_1$            | $T_2$                  | $T_1$           | $T_2$                         | $T_1$           | $T_2$           | $T_1$           | $T_2$           |
| ROI   |                  |                        |                 |                               |                 |                 |                 |                 |
| 1     | 508 $\pm$ 34     | 55 $\pm$ 3             | 501 $\pm$ 26   | 61 $\pm$ 2                   | 596 $\pm$ 21   | 76 $\pm$ 2     | 621 $\pm$ 61 (9) | 58 $\pm$ 4 (9) |
| 2     | 460 $\pm$ 33     | 55 $\pm$ 3             | 458 $\pm$ 20   | 57 $\pm$ 3                   | 596 $\pm$ 19   | 77 $\pm$ 3     | 561 $\pm$ 12 (21) | 73 $\pm$ 2 (21) |
| 3     | 475 $\pm$ 30     | 56 $\pm$ 4             | 475 $\pm$ 32   | 58 $\pm$ 4                   | 595 $\pm$ 27   | 84 $\pm$ 4     |
| 4     | 495 $\pm$ 33     | 57 $\pm$ 5             | 487 $\pm$ 38   | 58 $\pm$ 5                   | 629 $\pm$ 24   | 85 $\pm$ 5     |
| Mean  | 485 $\pm$ 33     | 56 $\pm$ 4             | 480 $\pm$ 30   | 59 $\pm$ 4                   | 604 $\pm$ 23   | 81 $\pm$ 4     |

| 3T    | Estimated values | Drift-corrected values | Reference values | Literature-published values |
|-------|------------------|------------------------|-----------------|-----------------------------|
|       | $T_1$            | $T_2$                  | $T_1$           | $T_2$                       |
| ROI   |                  |                        |                 |                             |
| 1     | 678 $\pm$ 33     | 51 $\pm$ 2             | 664 $\pm$ 35   | 53 $\pm$ 2                   | 771 $\pm$ 19   | 68 $\pm$ 2     | 832 $\pm$ 1 (22) | 80 $\pm$ 1 (22) |
| 2     | 660 $\pm$ 42     | 50 $\pm$ 3             | 642 $\pm$ 39   | 53 $\pm$ 3                   | 781 $\pm$ 18   | 70 $\pm$ 3     | 1084 $\pm$ 45 (23) | 69 $\pm$ 3 (23) |
| 3     | 636 $\pm$ 30     | 50 $\pm$ 2             | 624 $\pm$ 29   | 53 $\pm$ 2                   | 771 $\pm$ 16   | 69 $\pm$ 2     | 781 $\pm$ 61 (24) | 65 $\pm$ 6 (24) |
| Mean  | 658 $\pm$ 36     | 50 $\pm$ 2             | 643 $\pm$ 35   | 53 $\pm$ 2                   | 774 $\pm$ 18   | 69 $\pm$ 2     |

Note: The mean $T_1$ and $T_2$ values at 1.5 T were calculated for 1 slice of the brain by averaging over 4 regions of interest (ROIs) (each around 150 voxels) in white matter on corresponding $T_1$ and $T_2$ maps. The mean $T_1$ and $T_2$ values at 3 T were calculated for 1 slice of the brain by averaging over 3 ROIs (each around 100 voxels) in white matter on corresponding $T_1$ and $T_2$ maps.

$^a$Numbers in parentheses are reference citations.

in Table 2 for the estimated, drift-corrected, reference, and literature-published $T_1$ and $T_2$ values.

After drift correction, $T_1$ values decreased by about 1% compared with the uncorrected values, and $T_2$ values increased by about 5% compared with the uncorrected values (Figure 4E,F and Table 2). The $B_0$ values decreased by about 50%, and the corrected $B_0$ map resembles the reference $B_0$ map acquired right before the PLANET acquisition. The RF phase maps almost did not change after drift correction.

3.2.2 | 3 T

A spatially inhomogeneous drift was observed over the same 11-minute PLANET acquisition in the brain of another healthy volunteer at 3 T, with a maximum value of 10 Hz for the selected slice (Figure 5A). The $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ maps before and after linear drift correction, the banding-free magnitude, and the reference $T_1$ and $T_2$ maps, and deviations quantifying the amount of linear drift correction performed on all parameters are shown. The results of the ROI analysis are given in Table 2. Similar to the results at 1.5 T, the $T_1$ values after drift correction did not change much; they locally decreased by about 2% compared with the uncorrected values in the area with more pronounced drift. The $T_2$ values were more sensitive to drift, and after drift correction they increased by about 5%-6% compared with the uncorrected values in the area with more pronounced drift (Figure 5E,F and Table 2). The $B_0$ values decreased by about 50%, and the corrected $B_0$ map resembles the reference $B_0$ map acquired just before the PLANET acquisition. The RF phase maps did not change much after drift correction.

A remaining underestimation of about 20% in $T_1$ values and about 30% in $T_2$ values compared with the reference values are found in Figures 4 and 5 and Table 2.

3.3 | Simulation results

3.3.1 | Single-component phase-cycled bSSFP signal model of the phantom

Relative errors and SDs in $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ estimates for a single-component signal model of the phantom are presented in Figure 6, affected by linear drift (Figure 6A,B) and after applying drift correction (Figure 6C,D). As shown, drift induced errors depend on the choice of FA and TR. For the combination of FA $= 30^\circ$ and TR $= 10$ ms, which was used in the experimental setup, the quantitative analysis of the errors is presented in Table 3. The $T_1$ values are overestimated due to drift by about 4% compared with the true values; $T_2$ values are underestimated due to drift by about 8% compared with the true values; $\Delta f_0$ values are overestimated due to drift by about 100%; and $\phi_{RF}$ values are underestimated due to drift by about 5%. After applying the proposed drift-correction algorithm, relative errors in all estimated...
parameters are almost zero, which demonstrates an accurate performance of drift correction. The SDs in all estimated parameters are not affected by drift correction much and are below 5%.

These results are in agreement with the experimental results for the phantom shown previously: The simulated expected errors due to drift match the calculated errors in the estimated parameters.
3.3.2 Two-component phase-cycled bSSFP signal model

The simulation results for a two-component signal model of WM are shown in Figure 7. Relative errors in $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ are shown for 3 cases: no drift, linear drift, and after applying the drift-correction algorithm. The errors in the estimated parameters depend on the choice of FA and TR. As we showed in a previous study, in WM brain tissue the PLANET postprocessing results in systematic errors in estimated $T_1$, $T_2$, $\Delta f_0$, and $\phi_{RF}$ values due to the presence of a second myelin-related component in WM. Here we can observe similar behavior for the case without drift.

For the combination of FA = 20º and TR = 10 ms, which was used in the experimental setup, the quantitative analysis of the errors is presented in Table 3. The $T_1$ values are underestimated by 30% without drift, underestimated by 29.5% in the presence of drift, and underestimated by 30.5% after drift correction. The $T_2$ values are underestimated by 35% without drift, underestimated by 39% in the presence of drift, and underestimated by 34.5% after drift correction. The $\Delta f_0$ values are overestimated by 14% without drift, overestimated by 58% in the presence of drift, and overestimated by 10% after drift correction. The $\phi_{RF}$ values are overestimated by 20% without drift, overestimated by 25% in the presence of drift, and overestimated by 23% after drift correction.

The drift correction performed on all estimated parameters predicted by the simulations for the combination of TR = 10 ms and FA = 20º is similar to the drift correction performed experimentally in the brain: After drift correction, $T_1$ values decreased by about 1% compared with the drift-corrected values; $T_2$ values increased by about 5% compared with the drift-corrected values; $\Delta f_0$ values decreased by about 48%; and $\phi_{RF}$ values decreased slightly by about 1.5%. In all cases, drift-induced errors were corrected.
T 1 values were overestimated due to drift by about 80% compared with the corresponding reference values. The variance in the estimated parameters only slightly changed after drift correction. We demonstrated that both linear and exponential correction algorithms performed identically. The linear model for temporal evolution of the drift on a short time scale (0-15 minutes) may be a fair approximation of the exponential drift in the experiments reported in this paper. Drift-induced errors in T 1, T 2, Δ f 0, and φ RF estimates in a phantom were successfully corrected by applying the drift-correction algorithm. These results obtained experimentally were verified by numerical simulations for a similar setup: The bias and variance in all parameter estimates predicted by simulations matched the ones calculated using the experimental data of the phantom.

The investigation of the drift effects in the human brain showed that similar drift of about 10 Hz over the 11-minute duration of the PLANET acquisition had a significant effect only on the estimated Δ f 0 values: An overestimation of about 50% in Δ f 0 values was caused by drift. The other quantitative parameters were only affected slightly: The drift induced an overestimation of about 1% in T 1 estimates, an underestimation of about 5% in T 2 estimates, and an overestimation of about 5% in φ RF estimates. The errors in the quantitative parameters calculated in the brain were in agreement with errors predicted by simulations for a similar experimental setup. The proposed drift-correction algorithm performed well and corrected the errors caused by drift. However, the remaining underestimation by about 20%-30% in T 1 and T 2 values compared with the reference and literature published values, which can be found in Figures 4 and 5 and Table 2, is not caused by B 0 drift. It is caused by the effect that in WM tissue where multiple components are present, a single-component PLANET model is not valid, as we already pointed out in a previous study.13 Obviously, such underlying errors were not and cannot be corrected by the drift-correction algorithm. Keep in mind that any other techniques that assume a single-component relaxation model will fail in this case as well.

The severity of drift effect depends on the field strength, history of gradient activity and heating of metallic components of the scanner. PLANET acquisition time, the used gradient mode, shimming, and more, which vary among different systems and over time. Even though the errors in estimated quantitative parameters caused by drift in human brain are small (1%-5%) compared with the errors caused by the presence of multiple components (about 30% underestimation), as we have shown in this study, they cannot be predicted and can potentially affect reproducibility of the results, as drift effects are generally not reproducible. We have now shown that the drift-induced errors can be successfully corrected by applying the proposed drift-correction algorithm. Acquiring 2 quick low-resolution reference B 0 maps before and after the PLANET acquisition
is generally a simple direct way to correct for drift and improve the quantitative parameter estimation using the PLANET method.

5 CONCLUSIONS

We have demonstrated that the PLANET method is sensitive to B0 drift. Although there may be no directly visible B0 drift-related artifacts on the estimated parameter maps, drift can induce errors in these parameters. In the phantom, which can be described with a single-component signal model, drift induced significant errors in the estimated parameters. However, in the human brain, where multiple components are present, drift had only a minor effect. We have now shown that the drift-induced errors can be successfully corrected by applying the proposed drift-correction algorithm for both cases of a single-component and two-component signal model.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**TABLE S1** Quantitative results from the phantom experiment (the reference, estimated, and drift-corrected T1, T2, and Δf0 values) and the relative errors in estimated and drift-corrected T1, T2, and Δf0 values

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