

# Reducing $t_1$ Noise Through Rapid Scanning

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## Abstract

The so-called  $t_1$  noise, which arises due to random instabilities in the spectrometer hardware, remains the primary source of noise that limits the sensitivity of most 2D NMR experiments, particularly in the expanding group of solid-state NMR methods that utilize dipolar-recoupling. In this communication we revisit the relationship between the signal intensity and the  $t_1$  noise produced. It is shown that since the latter scales linearly with the signal strength, the use of a conventional relaxation delay of  $1.3T_1$  may prove far from optimal. In cases where the fluctuations occur on a shorter timescale than the recycle delay, a considerably shorter relaxation delay should be used to maximize the time sensitivity in a 2D experiment than what is used to maximize the sensitivity in 1D. This is demonstrated with the acquisition of  $^1\text{H}\{^{13}\text{C}\}$  Dipolar-mediated Heteronuclear Multiple-Quantum Correlation (D-HMQC) type spectra in which the sensitivity could be nearly doubled by choosing a very short relaxation delay corresponding to  $0.2T_1$ .

## Keywords

2D NMR,  $t_1$  noise, Spin-lattice relaxation, D-HMQC, Solid-state NMR

One of the main factors limiting the application of advanced two-dimensional (2D) nuclear magnetic resonance (NMR) methods is the prevalence of  $t_1$  noise. This noise, generally, occurs due to various instrumental instabilities, which lead to random fluctuations of NMR intensities between the scans during the acquisition of the 2D dataset.[1] As a result, the Fourier-transformed 2D spectrum exhibits ridges of intense noise along the indirect dimension, wherever a peak appears in the directly-detected dimension. Common sources of  $t_1$  noise include temperature changes, magnetic field fluctuations, as well as instabilities of radiofrequency (rf) power and phase.[2] Despite the dramatically improved stability of modern NMR spectrometers, this artifact can significantly reduce the overall signal-to-noise ratio (SNR) of an otherwise sensitive experiment.

A number of solutions have been reported for reducing  $t_1$  noise, including various post processing methods[3,4,5] and spreading the  $t_1$  noise more thinly along F1 through oversampling.[6] The  $t_1$  noise from particularly strong resonances, such as those originating from solvents, can be further suppressed through presaturation.[7] Recently, Mo et al. have also demonstrated that  $t_1$  noise in lengthy 2D NOESY spectra could be significantly reduced if the experiment were cut into  $N$  shorter experiments, each consisting of  $1/N$  scans.[8] This strategy succeeds in reducing the  $t_1$  noise resulting from slow changes in the magnetic field and temperature, which carry a smaller weight when the experiment is concluded quickly. The  $t_1$  noise may also be minimized by carefully managing the overall stability of the spectrometer performance and maintaining constant sample and ambient temperatures.[9]

In the case of magic-angle-spinning (MAS) solid-state NMR (SSNMR), by far the most important source of  $t_1$  noise is the instability in the rotor spinning.[10] The long-established methods relying on cross-polarization (CP) and spin-diffusion-based approaches are reasonably insensitive to the MAS frequency and the rotor phase.[9,10]

However, the rotation frequency can have a large impact on the signal amplitude when a recoupling experiment is used to acquire dipolar heteronuclear multiple-quantum correlation (D-HMQC)[11,12] or double-quantum single-quantum (DQ/SQ)[7] correlation experiments. The so-called non-“ $\gamma$ -encoded” sequences are particularly sensitive, as these require a precise control of the MAS rotor’s phase with respect to the timing of recoupling sequences. Changes in the MAS frequency (albeit not phase) can also alter the efficiency of these sequences as they depend on the ratio of the rf power and the rotation frequency being preserved.[13] As a result of these instabilities,  $t_1$  noise of this type is typically seen to increase as a function of the  $t_1$  evolution period. Lastly, secondary motional modes of the rotor, such as the in-out mode, affect the tuning of the probe and lead to changes in the rf power and phase from scan to scan. These sources of instabilities occur on a timescale that is shorter than the recycle delay and cannot, thus, be eliminated by the approach of Mo et al.[8] Recently, Nagashima et al. have attempted to address one of these sources of  $t_1$  noise, namely the sensitivity to the rotor phase, with their dipolar-heteronuclear universal-quantum correlation (D-HUQC) which makes use of  $\gamma$ -encoded dipolar recoupling.[14]

The abovementioned D-HMQC techniques have been recently gaining remarkable popularity as they are far more robust with respect to quadrupolar interactions and offset than CP-based approaches since only two  $90^\circ$  pulses are required on the indirect channel. For instance, D-HMQC experiments allow for the measurement of correlation spectra between spin-1/2 nuclei and quadrupolar nuclei,[15,16,17] between pairs of quadrupolar nuclei,[18] and to spin-1/2 nuclei with large chemical shift anisotropies.[19,20] The  $t_1$  noise is therefore, once again, an important limitation for the application of 2D SSNMR spectroscopy.

The  $t_1$  noise is perhaps best described with the synonym: multiplicative noise ( $N_{\text{mult}}$ ).[1] Namely, unlike conventional, additive, noise ( $N_{\text{add}}$ ), which is constant and independent of the NMR response,  $t_1$

noise depends directly on the intensity of the NMR signal. This is an important distinction since most 2D SSNMR experiments are performed in such a way that maximizes the sensitivity in F2 and thus also increases the  $t_1$  noise along F1. For example, the intensity of the NMR signal in a single scan ( $S$ ) following saturation is given by:

$$S = S_{\text{eq.}} \left( 1 - \exp\left(\frac{-d_1}{T_1}\right) \right), \quad (1)$$

where  $d_1$  is the recycling delay,  $T_1$  is the spin-lattice relaxation time and  $S_{\text{eq.}}$  is the amplitude of signal at equilibrium, per scan. When accounting for the fact that additive noise scales only as the square root of the number of scans while the signal scales linearly, the time averaged  $SNR$  is given by:

$$SNR = \frac{S_{\text{eq.}} \left( 1 - \exp\left(\frac{-d_1}{T_1}\right) \right)}{\langle N_{\text{add.}} \rangle \sqrt{d_1}}, \quad (2)$$

where  $N_{\text{add}}$  corresponds to the noise level in a single scan, and is defined as a variance of the noise over all data points

$$\langle N_{\text{add.}} \rangle = \frac{1}{n} \sqrt{\sum_{i=1}^n N_i^2} \quad (3)$$

with  $n$  denoting the number of data points and  $N_i$  the noise contribution to the  $i^{\text{th}}$  data point. Independently of  $S_{\text{eq.}}$  and  $N_{\text{add.}}$ , expression 2 has one maximum at  $d_1/T_1$  of ca. 1.3.[21] In the absence of  $t_1$  noise, the best choice for  $d_1$  is thus  $1.3T_1$ , which is commonly used to maximize the sensitivity per unit of time.

In the presence of multiplicative noise equation 2 is no longer valid and its use can lead to important sensitivity losses. The noise level in F1 can be determined as follows:

$$\langle N_{\text{F1}} \rangle = \sqrt{\langle N_{\text{add.}} \rangle^2 + \langle N_{\text{mult.}} \rangle^2}, \quad (4)$$

with  $N_{\text{mult}}$  expressed as:

$$\langle N_{\text{mult.}} \rangle = x \langle N_{\text{add.}} \rangle \left( 1 - \exp\left(\frac{-d_1}{T_1}\right) \right), \quad (5)$$

where  $x$  is the ratio between the  $t_1$  and  $t_2$  noise levels at equilibrium (i.e. with a recycle delay  $> 5T_1$ ) and corresponds to the hypothetical multiplicative noise level from a single scan. This choice of this parameter was made as it renders the solution of the subsequent equations independent of  $S_{\text{eq.}}$  and the exact noise levels. In direct analogy to equation 2, we can then express the signal-to-noise ratio in the F1 dimension of a 2D NMR experiment as:

$$SNR = \frac{S_{\text{eq.}} \left( 1 - \exp\left(\frac{-d_1}{T_1}\right) \right)}{\langle N_{\text{add.}} \rangle \sqrt{d_1} \sqrt{1 + x^2 \left( 1 - \exp\left(\frac{-d_1}{T_1}\right) \right)^2}}. \quad (6)$$

If we then take the derivative of equation 6 over  $d_1$  we can determine the function's maximum and determine the following relationship between  $x$  and the relaxation delay that maximizes sensitivity per unit of time:

$$x = \frac{\exp\left(\frac{d_1}{T_1}\right) \sqrt{\left(\exp\left(\frac{d_1}{T_1}\right) - 1\right) \left(-\exp\left(\frac{d_1}{T_1}\right) + 2\frac{d_1}{T_1} + 1\right)}}{\left(\exp\left(\frac{d_1}{T_1}\right) - 1\right)^2}. \quad (7)$$

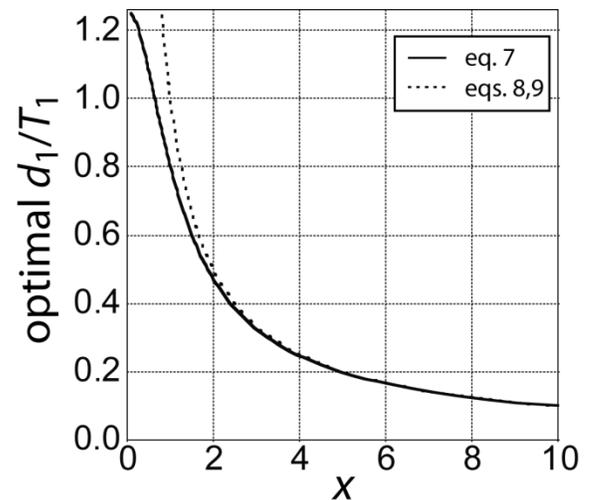
This relationship, of course, reproduces the expected  $d_1/T_1$  ratio of c.a. 1.3 when  $x$  is equal to 0 and also suggests the use of shorter relaxation delays when  $x > 0$ . Unfortunately, it is not possible to isolate  $d_1$  in order to have a convenient, and exact, closed-form solution to equation 7. If we assume that  $x$  is large (and thus  $d_1/T_1$  is short) it is possible to considerably simplify equation 7 using a Taylor expansion with a first term equal to:

$$x = \frac{T_1}{d_1}. \quad (8)$$

This relationship nearly perfectly reproduces equation 7 when  $x > 2$  (see Figure 1). Accordingly, in cases where  $t_1$  noise is significant, the relaxation delay should be set to the following value in order to maximize the  $SNR$  in the F1 dimension:

$$d_1 = \frac{T_1}{x} = \frac{\langle N_{\text{add.}} \rangle}{\langle N_{\text{mult.}} \rangle_{\text{eq.}}} T_1. \quad (9)$$

The factor  $\langle N_{\text{add.}} \rangle / \langle N_{\text{mult.}} \rangle_{\text{eq.}}$  includes the noise levels in F2 and F1 dimensions corresponding to a relaxation delay of  $5T_1$ , which can be easily measured. Note that our conclusion is counter to earlier suggestions that recycle delays of  $5T_1$  should be applied to minimize  $t_1$  noise, which seems to be unnecessary if proper presaturation is performed.[1] In cases when  $x$  is relatively small the sensitivity gains available by shortening the relaxation delay are minor and thus a relaxation delay of  $1.3T_1$  can be used. Equations 7 and 8,9 are plotted in Figure 1 where the relationship between the optimal relaxation delay and  $t_1$  noise level can be more clearly visualized.

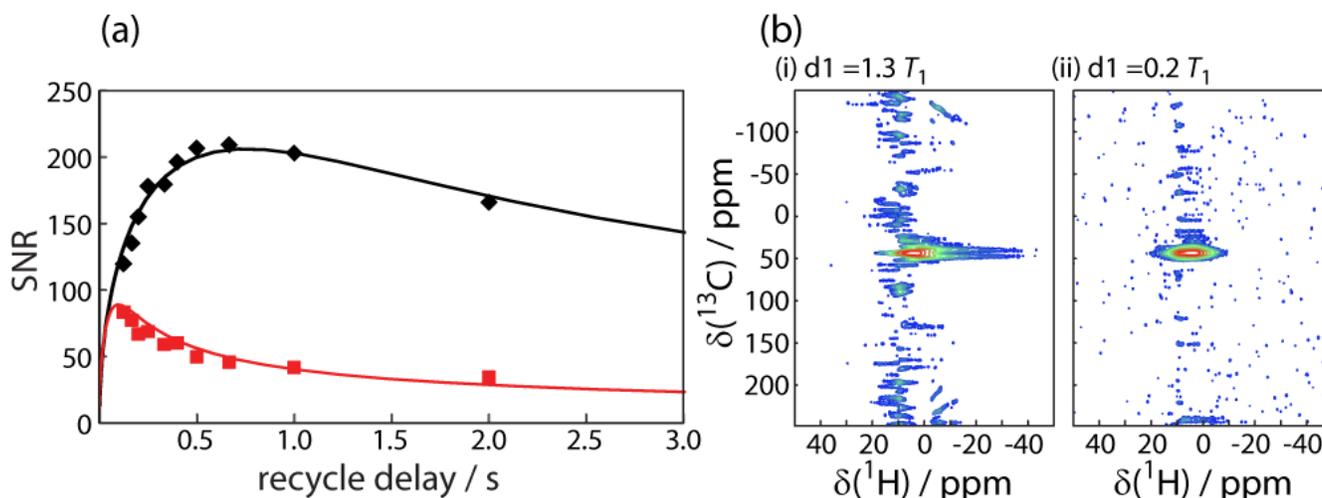


**Figure 1.** The relationship between the optimal relaxation delay, expressed as a fraction of the  $T_1$  relaxation time, and the importance of  $t_1$  noise ( $x$ ) is plotted. The exact relationship (equation 7, solid line) and our analytical approximation (equations 8 and 9, dotted line) are compared.

To demonstrate the improvements in  $SNR$  from rapid scanning, we have acquired  $^1H\{^{13}C\}$  D-HUQC spectra of  $^{13}C,^{15}N$ -enriched glycine, using a 1.3-mm MAS probe with poor spinning stability (*vide infra*), a spinning frequency of  $\sim 40$  kHz and relaxation delays varied between 0.125 s and 2 s. The  $T_1$  relaxation time was measured to be 0.6 s using a saturation recovery experiment. Presaturation was used in order to ensure that each scan initiated at the same steady-state. In all cases, the experiment time was maintained constant at 17 minutes. Unlike the seminal paper of Nagashima,[14] we chose to use an  $m = 2$  heteronuclear dipolar recoupling sequence ( $R18^5_2$ )[22] in order to decouple the  $^1H$  homonuclear dipolar coupling interactions during the heteronuclear recoupling. We have plotted the  $SNR$  that were obtained along F1 and F2 in Figure 2a and fit them using equations 2 and 5 with  $S_{eq}/N = 250$  and  $x = 6$ . As can be seen from the data in Figure 2, the relaxation delay which provides the highest signal-

to-noise ratio for this 2D experiment is of only  $0.2 T_1$  rather than  $1.3T_1$ . In this case, the use of the more conventional relaxation delay of  $1.3T_1$  would have led to a 50% reduction in  $SNR$ . This can be clearly seen in Figure 2b where we compare the 2D spectra acquired with relaxation delays of  $1.3T_1$  and  $0.2T_1$ . Here, it is also worth mentioning that in experiments with severe  $t_1$  noise the optimal recycling delay may become shorter than the shortest allowable duty cycle. Of course, in those situations the shortest safe recycling delay should be used, which was the case in our example.

In summary, we have demonstrated that that in case of 2D NMR measurements with strong  $t_1$  noise originating from fluctuations that are faster than the recycle delay, far shorter relaxation delays than the typically used  $d_1 = 1.3T_1$  are required to maximize the sensitivity per unit of time. A simple expression is given in order to determine the appropriate value.



**Figure 2.** The signal-to-noise ratios measured along the F2 (black diamonds) and F1 (red squares) dimensions of  $^1H\{^{13}C\}$  D-HUQC experiments lasting 17 minutes are plotted as a function of the recycling delay (a). The data are fit using equations 2 and 5 with values of  $S_{eq}/N = 250$ ,  $x = 4.5$ , and  $T_1 = 0.6$  s. Example  $^1H\{^{13}C\}$  D-HUQC spectra are shown in (b) with recycling delays of  $1.3T_1$  (i) and  $0.2T_1$  (ii). The ‘floor’ is set to the same relative level in each case. As can be seen, although the use of a recycling delay lasting  $1.3T_1$  yields the highest sensitivity in F2, a recycling delay of  $0.2 T_1$  yields the highest overall sensitivity.

### Experimental

All experiments were performed on a Bruker AVANCE III 400 MHz SSNMR spectrometer using a 1.3-mm MAS probe. This probe, which was designed for rapid sample changing at low-temperatures, suffers from additional instabilities caused by the VT and Venturi gas flows that increase the  $t_1$  noise. For the  $^1H\{^{13}C\}$  D-HUQC experiments a  $^{13}C,^{15}N$ -enriched glycine sample, purchased from ISOTEC, was used. The sample spinning frequency was set to 40 kHz and the rf magnetic fields for the  $^1H$  and  $^{13}C$  pulses were set to 100 kHz while those for the  $R18^5_2$  recoupling were of 180 kHz ( $4.5\nu_R$ ). The evolution in the indirect dimension was synchronized with the rotation frequency and a total of 128  $t_1$  increments were acquired for each spectrum. A minimum of 4 scans were acquired with a recycling delay [1] J. Granwehr, Multiplicative or  $t_1$  noise in NMR spectroscopy, Appl. Magn. Reson. 32 (2007) 113-156.

of 2 s and this number was increased to 64 when the recycling delay was decreased to 0.125 s. Purely absorptive phase 2D lineshapes were obtained using the States-TPPI method.

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