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Real-Time Noise Bias Compensation in Magnitude-Accumulated TD and FFC-NMR Relaxometry

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1. Introduction

Magnitude-mode (absolute value) detection is widely adopted in TD and Fast Field Cycling (FFC) NMR relaxometry to reduce sensitivity to phase instabilities and magnetic field fluctuations. By accumulating the absolute value of the complex signal over many scans, stable measurements can be obtained even under unfavourable field conditions.

However, this approach introduces a well-known systematic artefact. The statistical origin lies in the Rician distribution of the detected signal: in the absence of true magnetization, the distribution reduces to Rayleigh statistics, producing a strictly positive mean proportional to the noise standard deviation σ.

When signals are accumulated coherently over many scans, this positive bias accumulates proportionally, generating a field-independent offset that cannot be removed by simple baseline subtraction. Practical consequences include:

- Systematic underestimation of T_1 and T_2 values
- Distortion of long-time relaxation behaviour and non-zero plateau
- Masking of weak components in multi-exponential analysis.

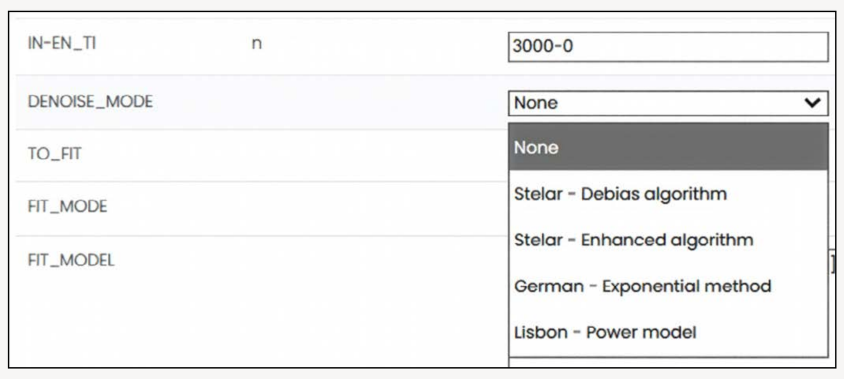
2. Methods

The noise standard deviation σ is estimated experimentally from reference acquisitions performed without RF excitation, under identical experimental conditions such as receiver gain and bandwidth settings. Based on this estimate, selectable correction algorithms are applied either in real time during acquisition or retrospectively in post-processing.

Three debiasing algorithms are implemented and selectable at runtime:

Algorithm	Approach	Reference
Stelar Enhanced	Correction for accumulated modulus signals	*Martini et al., 2001* [1]
German Exponential	Rician distribution-based correction (exponential approximation)	*Gudbjartsson & Patz, 1995* [2]
Lisbon Power Model	Power-law correction developed at IST Lisbon (novel)	*Figueirinhas & Sebastião* [3]

▲ TABLE 1.
Debiasing algorithms integrated into the modular correction framework. All three are selectable at runtime.

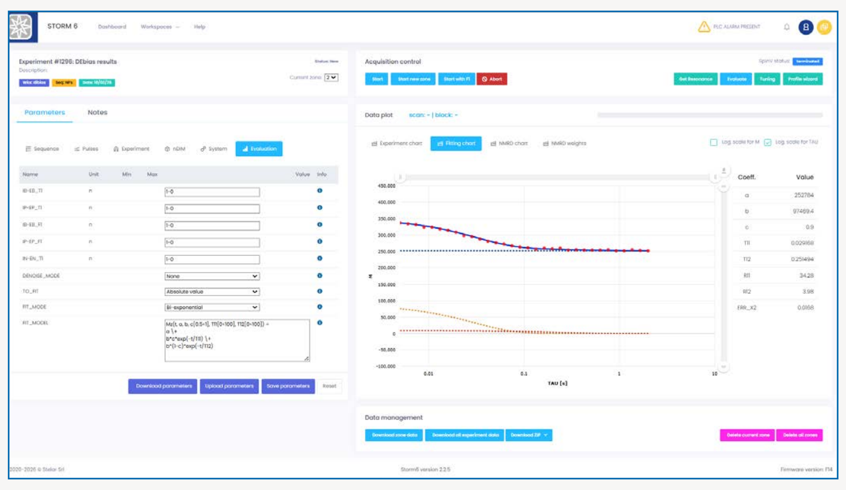


▶ IMAGE 1.
Screenshot of the algorithm selector dropdown (DENOISE_MODE: None / Stelar Debias / Stelar Enhanced / German Exponential / Lisbon Power Model).

3. Results

Validation was performed on simulated bi-exponential datasets (TD-NMR, Seq: NPs - Non-Polarized sequence) under varying SNR conditions, including cases with unequal noise variance between the Real and Imaginary (I and Q) channels.

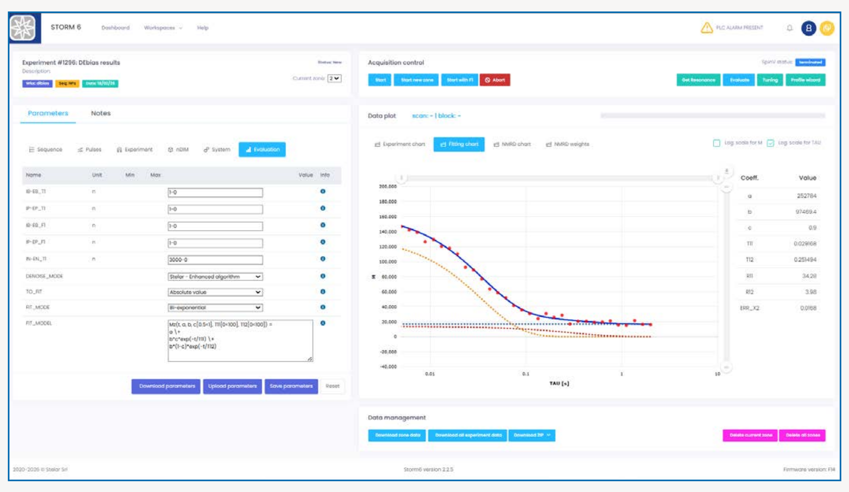
Without correction: the accumulated magnitude signal presents a significant positive offset, preventing convergence of the fit towards the physically expected zero baseline. Fitted parameters are systematically biased (T_{11} = 0.029 s, T_{12} = 0.251 s) relative to ground truth (T_{11} = 0.03 s, T_{12} = 0.3 s), with ERRχ^2 = 0.0168. (The chi-squared statistic is defined as a weighted sum of squared deviations between the observed data and the model predictions, with weights given by the inverse of the noise variance).



◀ IMAGE 2:
Bi-exponential fitting without debiasing, positive offset prevents convergence to zero.

After applying the Stelar Enhanced Algorithm: the debiased signal converges correctly toward zero at long inversion times (Figure 3), in contrast to the residual offset observed in the uncorrected data (Figure 2). The fitting quality improves significantly, as evidenced by the reduction of the baseline offset and improved agreement with the model. Quantitatively, this results in a decrease in the fitting residuals and a more stable estimation of relaxation components. Consequently, individual relaxation components are more clearly resolved, and the reliability of the extracted parameters is enhanced. The correction selectively removes the systematic offset while preserving stochastic fluctuations, thereby enabling accurate uncertainty estimation.

When the noise power ratio between I and Q channels remains within a moderate range and SNR exceeds approximately 2, corrected signals converge reliably. Exponential fit convergence is restored and relaxation parameter estimation is stabilized, particularly in the slow-decay regime.



◀ IMAGE 3:
Fitting result after Stelar Enhanced Algorithm, signal converges to zero, components resolved

4. Conclusions

- A modular noise debiasing framework has been successfully developed and validated for TD and FFC-NMR relaxometry.
- Three selectable correction algorithms address the systematic positive bias from magnitude-mode signal accumulation, including a novel power-law model developed at IST Lisbon.
- Physically correct signal convergence is restored and T_1 parameter estimation is improved without altering the intrinsic signal structure.
- The framework operates in real time or post-processing and is applicable to any NMR relaxometry platform employing magnitude accumulation.
- Particularly valuable in low-SNR regimes and multi-exponential analysis scenarios.

Keywords

- FFC-NMR
- TD-NMR
- noise bias correction
- magnitude detection
- Rician noise
- T_1 relaxometry
- debiasing algorithm

References

[1] H. Gudbjartsson & S. Patz, *Magn. Reson. Med.* **34**, 910–914 (1995). https://doi.org/10.1002/mrm.1910340618
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