Ramsey Pulse Sequence Simulation
Estimating the Effect of Magnetic Field Fluctuations

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Measuring Magnetic Field

How does the measured field behave?

- Temporal fluctuations
- Spatial inhomogeneity

Using phone (Phyphox) as device

- Designed to measure Earth's magnetic field (compass)
- How suitable is a phone for such measurements?

Setup

Measuring the Earth's magnetic field

- Assumption: Earth field constant

$\rightarrow$ Statistic and systematic errors device specific

$\rightarrow$ Should allow more objective analysis

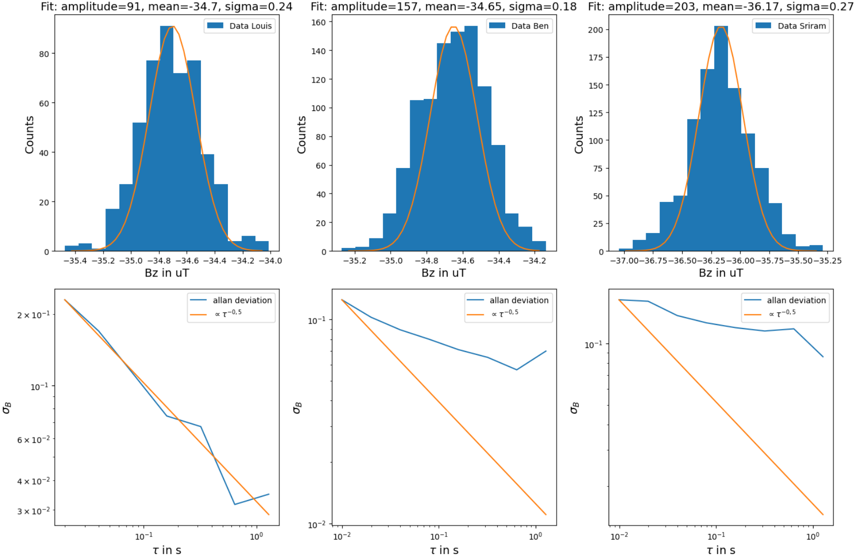
- Still, minimize environmental factors

$\rightarrow$ Place phone on floor in middle of large room (away from electronics, metal, etc.)

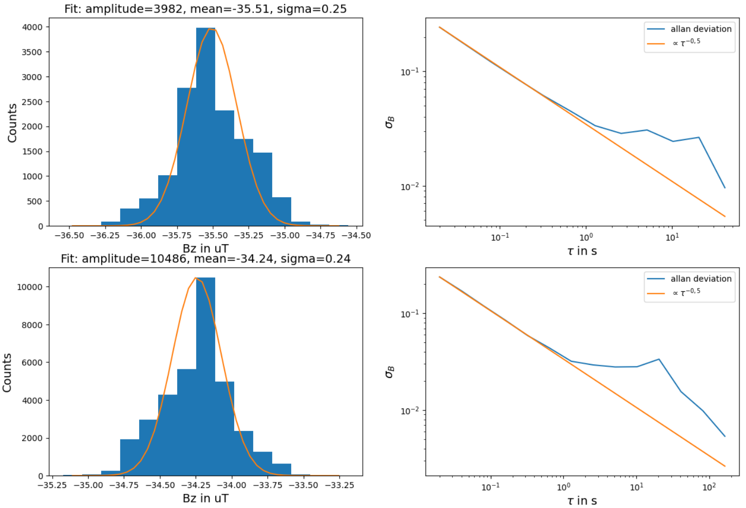
$\rightarrow$ Airplanemode (minimize interaction with EM-waves)

$\rightarrow$ Same positioning and orientation between devices

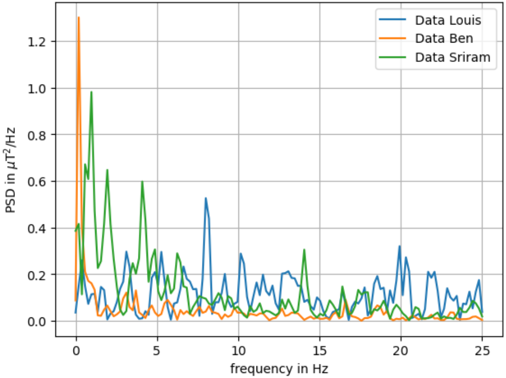
Distribution and Allan Variance

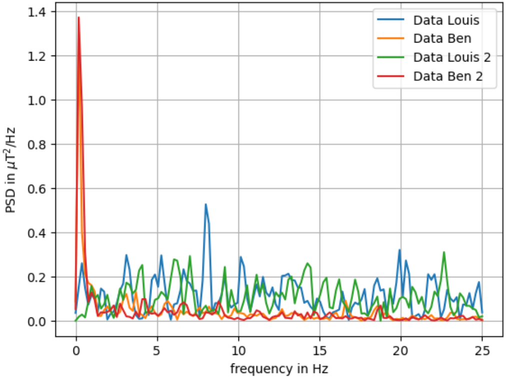


Longer Acquisition Times



PSD and Noise Floor





- Phone Louis: average RMS noise of 1.67 μT, and a minimal recommended sensitivity of 3.33 μT ar 95% confidence level
- Phone Ben: average RMS noise of 1.08 μT, and a minimal recommended sensitivity of 2.16 μT ar 95% confidence level

Next Step: Artificial Field

Inherent Problems

- Size of phone
- Uncertainty of sensor positioning
- Interaction between phone electronics and coil system

Conclusion

Is a phone suited for such measurements?

- 2.16 μT sensitivity

$\rightarrow$ Assuming fluctuations in μT range, not enough! (2018 [2])

- Systematic errors appear fast

$\rightarrow$ Average over short time scales

- Apart from other inherent problems

$\rightarrow$ Makes phone at the very least inconvenient

$\Rightarrow$ Looking for other sensors might be advantageous

Core Idea

Goal of the Simulation:

- Simulate a Ramsey Experiment including a realistic pulse sequence and variable magnetic field noise.
- Visualize Bloch trajectories, extract coherence time T_2, and thus observe the effect of magnetic field noise.
- Comparing the effect of magnetic field noise on Hyperfine and Optical Qubits by changing input parameters based on the used qubit transition
- Test whether the measured magnetic field fluctuations have a significant impact

Ramsey Pulse Sequence:

- The first $\pi/2$ pulse creates a superposition with a relative phase defined by the laser in the rotating frame
- Magnetic field noise (among other effects) creates phase diffusion
- The second $\pi/2$ pulse converts the accumulated phase into a measurable population difference
- Enables coherence characterization of qubits (T_2). *(Wineland et al., 1998 [1])*

Platform Comparison:

- Trapped-ion qubits (optical & hyperfine)
- Using parameter values from existing experimental setups
- Hyperfine qubit parameters from Hakelberg et al. (2018 [2])
- Optical qubit parameters from Chwalla (2009 [3])

Pulse Sequence

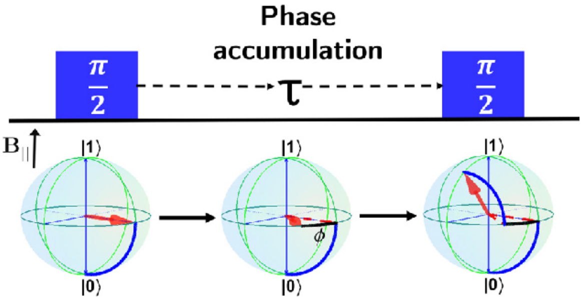


Figure: Ramsey Spin Sequence, Rembold et al. 2020[7]

Method Overview

Simulation chain:

1. Create artificial noise for simulation purposes
2. Build the pulse sequence
3. Solve the Lindblad Master Equation with a time-dependent Hamiltonian
4. Extract populations, Bloch trajectory, and ensemble averages
5. Fit Ramsey contrast to obtain T_2

Hamiltonian Setup

$$H_{rot} = \frac{\hbar}{2}(\Delta + \delta\omega(t))\sigma_z + \frac{\hbar}{2}\Omega(t)(cos(\phi)\sigma_x + sin(\phi)\sigma_y)$$

- Rotating wave approximation
- Δ is the laser detuning $\Delta = \omega_q - \omega_L$
- $\delta\omega(t) = \gamma_{\text{eff}}\,\delta B(t), \qquad \gamma_{\text{eff}} = \frac{\mu_1 - \mu_0}{\hbar}$ where γ_{eff} is the effective gyromagnetic ratio of the qubit transition. For hyperfine qubits this value is usually very small, while for optical qubits it is typically much larger.
- $\Omega(t)$ is the Rabi frequency (nonzero during the laser pulses for the Ramsey experiment)
- σ_{xyz} are the Pauli Operators and represent rotation around the axis of the subscript
- ϕ is the drive phase of the laser
- Formalism follows standard two-level system Hamiltonian *(Nielsen & Chuang, 2010 [4])*

Lindblad Master Equation

This is where decoherence comes in!

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H_{\mathrm{rot}}(t),\, \rho(t)] + \Gamma_1\left(\sigma_-\rho\sigma_+ - \frac{1}{2}\{\sigma_+\sigma_-,\, \rho\}\right) + \frac{\Gamma_\varphi}{2}(\sigma_z\rho\sigma_z - \rho)$$

- Describing the temporal evolution
- Using density matrix ρ to describe the state of the system
- First term: Commutator of density matrix and Hamiltonian
- First dissipator term: Energy relaxation (spontaneous decay / no thermal excitation) $\rightarrow T_1$
- Second dissipator term: Dephasing in the xy-plane
- Formal structure taken from standard Lindblad form *(Breuer & Petruccione, 2002 [5])*

Ornstein–Uhlenbeck (OU) Noise Generation

Key properties:

- Mean Reverting: $\mathbb{E}[x(t)] = x(0)e^{-t/\tau}$ - no long drifts!
- Autocorrelation: $C(\Delta t) = \sigma^2 e^{-|\Delta t|/\tau}$ Correlation decays exponentially
- Stationary variance: $\mathrm{Var}[x]_\infty = \sigma^2$ - fluctuations are well defined and constant

Exact discrete-time update:

$$x_{k+1} = e^{-\Delta t/\tau} x_k + \sigma \sqrt{1 - e^{-2\Delta t/\tau}}\, \eta_k, \quad \eta_k \sim \mathcal{N}(0, 1)$$

1. Uses exact sampling method for OU processes *(Gillespie, 1996 [6])*

Example Bloch Trajectory: Hyperfine Stable Qubit

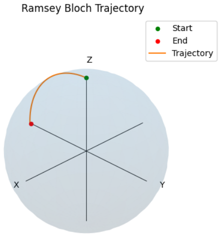


Figure: Bloch Trajectory with Wait Time of 0.1s

Ramsey Signal - Example 1

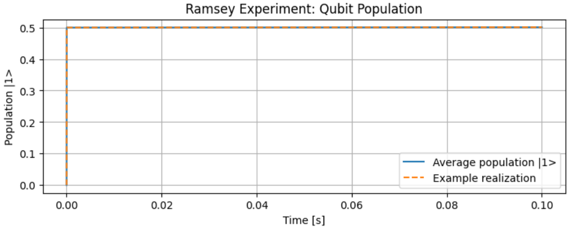


Figure: Population of Excited State after Ramsey Experiement

- Blue: Single Realization.
- Orange: Ensemble average.

Example Bloch Trajectory: Optical Qubit, less stable, with some noise

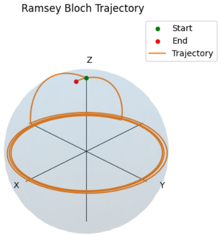


Figure: Bloch Trajectory for Wait Time of 1ms

Ramsey Signal- Example 2

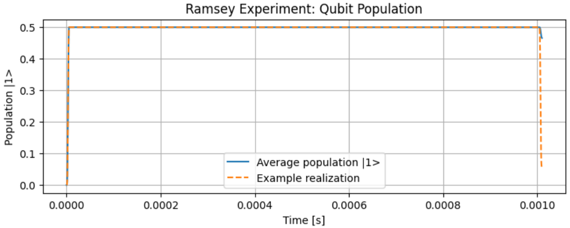


Figure: Excited State Population for Optical Qubit Simulation

- Blue: single realization.
- Orange: ensemble average.

Example Bloch Trajectory: Hyperfine Qubit, less stable, with noise

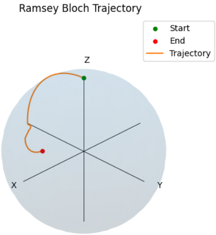


Figure: Bloch Trajectory for Wait Time of $10^{-4}s$

Ramsey Signal- Example 3

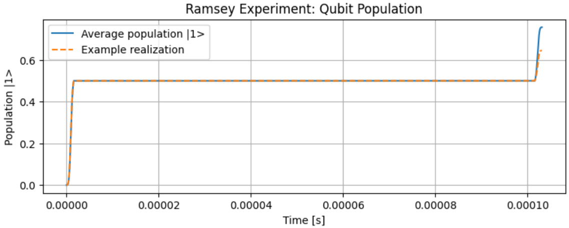


Figure: Excited State Population for noisy hyperfine qubit

- Blue: single realization.
- Orange: ensemble average.

Example Bloch Trajectory: Hyperfine Qubit, very noisy

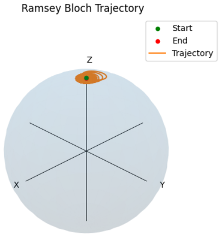


Figure: Bloch Trajectory of very noisy Hyperfine Qubit, Wait Time $10^{-3}s$

Ramsey Signal- Example 4

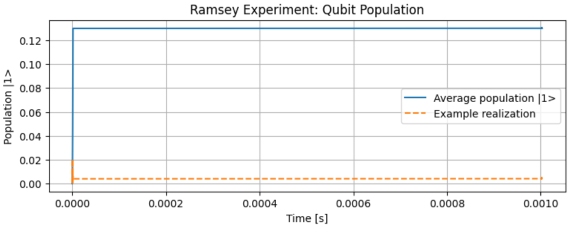


Figure: Excited state population for very noisy hyperfine qubit

- Blue: single realization.
- Orange: ensemble average.

Extracting T_2

- Running the same simulation with different wait times in between pulses
- Contrast - magnitude of the transverse component of the bloch vector

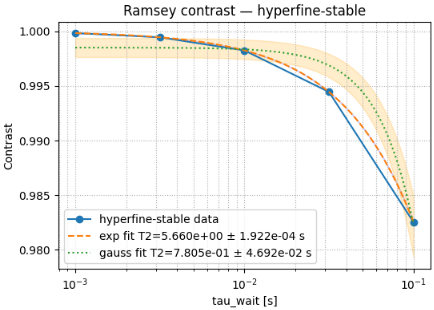
Fit contrast decay with:

$$C(t) = C_0 \exp\left(-\left(\frac{t}{T_2}\right)^2\right)$$

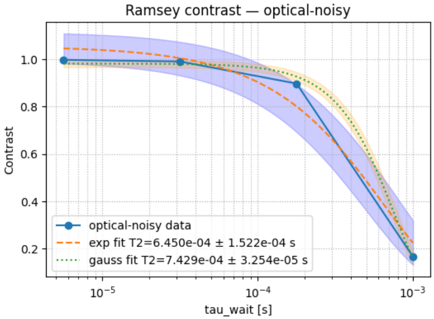
Fit result:

- Hyperfine Qubit 1 $T_2 = 5.660 \pm 1.922 * 10^{-4}$
- Optical Qubit $T_2 = 6.450 * 10^{-4} \pm 1.522 * 10^{-4}$
- Noisy Hyperfine Qubit $T_2 = 1.522 * 10^{-4} \pm 2.924 * 10^{-5}$
- Very noisy Hyperfine Qubit $T_2 = 9.005 * 10^{-5} \pm 1.525 * 10^{-5}$

Extracting T2

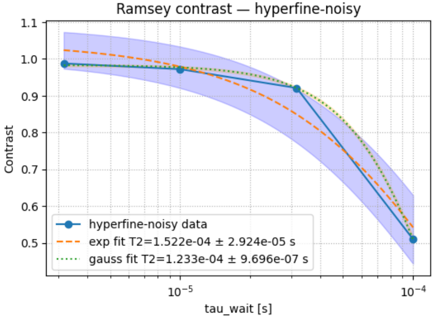


(a) T2 Example 1: Hyperfine Stable

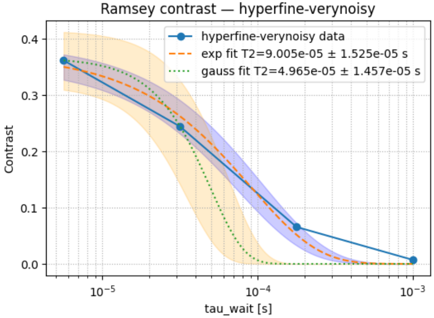


(b) T2 Example 2: Optical Qubit, Noisy

Extracting T2



(a) T2 Example 3: Hyperfine Qubit, Noisy



(b) T2 Example 4: Hyperfine Qubit, Very Noisy

Uncertainty Analysis

Statistical uncertainties:

- Finite number of realizations.
- Fit uncertainty

Systematic uncertainties:

- Ignoring other sources of noise.
- Two level atom is simplified
- Non-ideal $\pi/2$ pulses.
- Numerical timestep discretizations.

Reflection and Limitations

- Simulation currently not fully suited for simulating real lab setups
- Simulation captures key decoherence mechanisms but neglects many other factors
- Simulated noise does not match the full power spectrum of real magnetic noise.
- Missing longer term systematic effects such as heating of equipment
- Optical qubits especially have sensitivities to other noise which is ignored

Possible Improvements/ Dead ends

- Add other sources for decoherence / noise
- Improve computing time in order to run over more iterations, reduce statistical noise, decrease time steps
- Dead ends: Quiskit troubles, starting from scratch, underestimating the complexity of the simulation

Thank you!

References I

[1] D. J. Wineland et al., *Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions*, J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998). https://tf.nist.gov/general/pdf/1275.pdf

[2] F. Hakelberg et al., *Hybrid setup for stable magnetic fields enabling robust quantum control*, Scientific Reports 8, 13120 (2018). https://www.nature.com/articles/s41598-018-22671-5

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[4] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press (2010). https://doi.org/10.1017/CBO9780511976667

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[5] Breuer, Heinz-Peter Petruccione, Francesco. *The Theory of Open Quantum Systems.* (2006). https://doi.org/10.1093/acprof:oso/9780199213900.001.0001

[6] D. T. Gillespie, *Exact numerical simulation of the Ornstein–Uhlenbeck process*, Phys. Rev. E 54, 2084 (1996). https://doi.org/10.1103/PhysRevE.54.2084

[7] P. Rembold et al., *Quantum Optimal Control with Reinforcement Learning*, PRX Quantum 1, 020319 (2020). https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.1.020319