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Terranova-MRI Student Guide

Table of Contents & Sample Chapter

Preface

The purpose of this teaching manual is to provide a collection of self-contained student experiments that can be carried out using the Terranova-MRI apparatus. Each of these experiments will demonstrate and teach different principles of physics, NMR and MRI. They can be used as a unit or individually depending on the requirements of the course.

Each experiment contains an objective, background theory, a step-by-step guide to the experiment itself and a list of potential follow-up questions. Some of the follow-up questions will deliberately lead the student to consider topics that are covered in subsequent experiments as a means of providing continuity between the experiments. Throughout the experimental procedure questions will be posed to the student and some steps in the procedure will be left to the student to determine on their own. The intention is to make the student do some independent thinking and to require the student to extrapolate answers from the background information and the hints given.

The experiments are divided into three categories: Part I - Introductory Experiments, Part II – Earth's field NMR Experiments and Part III – Earth's field MRI Experiments. Part I is intended to take the student through the initial setup of the Terranova-MRI apparatus and the acquisition of a good quality NMR signal. These experiments focus in great detail on how to obtain a good quality NMR signal and explore the role of several important acquisition parameters and their effect on signal quality. Part II provides an overview of some of the fundamental topics of NMR. These include T_1, T_2 and T_2* relaxation time measurements, spin-echoes and multiple-echo sequences such as CPMG. Part III covers topics of interest in the field of MRI. These experiments cover basic 1D and 2D image acquisition using spin-echo, gradient echo and filtered back projection imaging methods, as well as more advanced topics such as image contrast.

An "appendix for the instructor" section is included with each experiment to provide the instructor with the answers to any advanced questions posed in the experiments and also to provide a more detailed description of the procedure steps that are left to the student to determine in the experiment. Thus the level of difficultly of each experiment can be tailored as desired. The appendix will also provide some example data. This data is included to provide the instructor with an idea of the type of results that should be obtained in each experiment.

Terranova-MRI EFNMR Student Guide
Meghan E. Halse, Magritek Limited, 2006

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SAMPLE CHAPTER

4. Spin-echoes and Spin-Spin (T_2) Relaxation

4.1. Objective

The object of this experiment is to learn about spin-spin relaxation in NMR and to observe the relationship between the spin-spin relaxation time constant, T_2, and the effective spin-spin relaxation time constant, T_2^*. The concept of a spin-echo will be introduced and used to demonstrate the difference between T_2 and T_2^*. The T_2 time constant for a bulk water sample will be measured using a spin-echo experiment.

4.2. Apparatus

The Terranova-MRI EFNMR system, consisting of the EFNMR probe, spectrometer and a controlling PC, will be used for this experiment. All experiments will be run from the *Prospa* software package. The sample is a 500 ml bottle of tap water.

4.3. Background Theory

4.3.1. Spin-Spin and Effective Spin-Spin Relaxation

The NMR signal arises from the phase coherence of an ensemble of precessing nuclear spins. The exponential decay of the signal is a consequence of the loss of phase coherence between the spins. One source of phase coherence loss is the relaxation process known as spin-spin relaxation (characterised by the T_2 relaxation time constant). Spin-spin relaxation is caused by the magnetic dipole coupling between two neighbouring spins. In the presence of a completely homogeneous field, spin-spin relaxation is the dominant source of phase coherence loss. Therefore the sampled signal, as a function of time is given by:

$$S(t) = S_0 \exp\left(-t/T_2\right) \qquad [4.1]$$

where S_0 is the initial signal magnitude at $t = 0$. For a bulk water sample, the T_2 time constant is typically on the order of a couple seconds and therefore the NMR signal from such a sample should, ideally, persist for a number of seconds. However, in practice, the magnetic field is not entirely homogeneous and therefore the loss of phase coherence is not solely due to spin-spin relaxation but is rather a combined effect of spin-spin relaxation and magnetic field inhomogeneity. Local magnetic field inhomogeneities introduce a range of Larmor frequencies across the sample. Each nucleus will precess at the Larmor frequency associated with its position. The overall phase coherence of the ensemble depends on all nuclei precessing at the same frequency. Therefore this dispersion of frequencies will result in a loss of phase coherence and hence signal decay.

To describe the combined relaxation effects, an effective spin-spin relaxation time constant, T_2* is defined, where γ is the gyromagnetic ratio of the observed nucleus and ΔB_0 is the magnetic field inhomogeneity.

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma\Delta B_0 \qquad [4.2]$$

Therefore the observed signal as a function of time in a situation with significant magnetic field inhomogeneity is given by:

$$S(t) = S_0 \exp\left(-t/T_2^*\right) \qquad [4.3]$$

where S_0 is the initial signal magnitude at $t = 0$. The phase coherence loss due to spin-spin relaxation is essentially irreversible, whereas the coherence loss due to magnetic field inhomogeneity *can* be reversed by generating a so-called *Hahn-echo* (or spin-echo).

4.4. Procedure

4.4.1. Getting Started

Run through the setup procedures from Experiments 1 & 2 to acquire a good quality FID of a large tap water sample. This process should include:

Shimming.
Setting the B_1 frequency to the Larmor frequency of the sample.
Tuning the coil to the Larmor frequency of the sample.
Determining the length of the 90° and 180° pulses.

4.4.2. Spin-Echoes

For the next section of this experiment the spin-echo pulse sequence in Figure 4.1 will be employed.

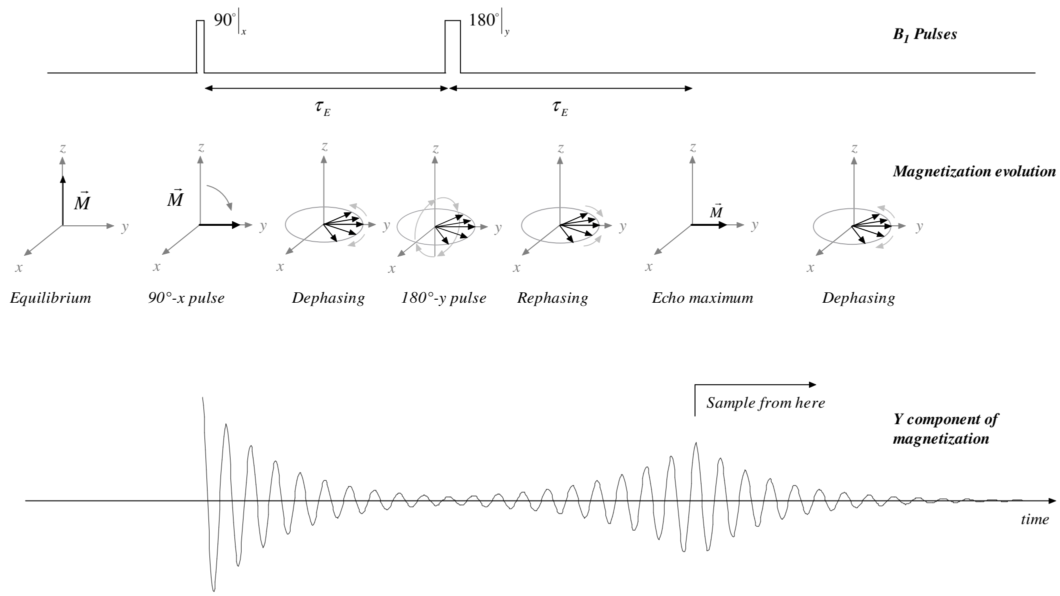

Figure 4.1. The spin-echo pulse sequence diagram.

The spin-echo sequence manipulates the phase coherence of an ensemble of excited spins. The first step in the experiment is the polarisation of the sample with a polarising pulse from the polarising coil, as is done in the simple pulse and collect experiment. This step is not shown in the above diagram.

The second step is to excite the sample with a 90° pulse. This results in the rotation of the bulk magnetic field vector into the transverse plane. In the subsequent delay time-period, τ_E, the magnetisation de-phases from the combined effects of spin-spin relaxation and magnetic field inhomogeneity. The former, caused by the random motion of the spins, is essentially irreversible whereas the latter can be reversed. Reversing the de-phasing due to magnetic field inhomogeneities is the goal of this basic spin-echo experiment.

At a time τ_E following the first 90° pulse, a 180° pulse is applied to the sample. This pulse flips the magnetic field vectors about a given axis in the transverse plane. During the subsequent time period, τ_E, the magnetisation re-phases and forms what is known as a spin-echo. Only the de-phasing that occurred as a result of magnetic field inhomogeneity will be re-focused.

Open the spin-echo experiment from under the EFNMR menu. The following dialog will appear.

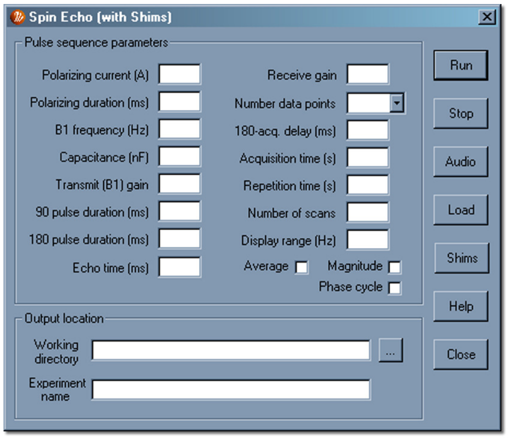

Figure 4.2 Spin-echo experiment dialog

The delays for this experiment must be chosen carefully, with attention given to how they interrelate. The time between the 90° pulse and the 180° pulse is called τ_E, the echo-time. The centre of the spin-echo is at a time, τ_E, after the 180° pulse. In Figure 4.1 the sampling commences at the centre of the echo and therefore the delay between the 180° pulse and the first sampled data point is τ_E. However, we would like to observe the entire echo and so we wish to sample as soon as possible after the 180° pulse. The acquisition delay, *acqDelay* (**180-acq. delay**), following the 180° pulse, must accommodate the ring down of the coil and should thus be at least 20 to 25 ms. If data is acquired for a time, t_{acq} (**acquisition time**), then the echo will fall in the centre of the acquisition window only if equation 4.4 is fulfilled.

$$t_{acq} = 2(\tau_E - acqDelay) \qquad [4.4]$$

The echo time must be chosen to be long enough to allow the user to view the entire echo and to allow for the complete relaxation of the signal excited by the 90° pulse. Inspect the signal, in the FID window, from a pulse and collect experiment. How long does it take for the signal to decay? Choose an echo time, τ_E, which is a bit longer than the signal persists in the FID window. Choose an acquisition delay of 25 ms and use these parameters to calculate an appropriate acquisition time. Run the experiment. You should observe an echo signal in the FID window. In order to see the echo clearly, try averaging 4 or 9 scans.

4.4.3. Magnetic Field Inhomogeneity and the FID

In this experiment the spin-echo sequence will be used to demonstrate the difference between T_2 and T_2* relaxation and to measure T_2. However, first we shall return to the pulse and collect experiment to observe the effect of magnetic field inhomogeneity on the FID and spectrum.

Acquire an FID of the tap water sample, using the pulse and collect experiment and the 90° pulse. Estimate the peak voltage of the FID signal. The FID signal decay can be described by an exponential decay with a single decay time constant. Estimate this time constant by finding the time it takes for the signal to decay to approximately 1/e (37%) of its initial value. Estimate the width of the peak in the spectrum and choose a frequency range for integrating the sample peak. Integrate under the sample peak in the spectrum to determine signal amplitude. Aside: The spectrum peak can be integrated using the 1D macro "integrate1D", which is found under the "1D" menu in the main *Prospa* window (see Figure 4.3.) In the 1D plot window, use the "Allow Region Selection" tool  to select a region around the sample peak.

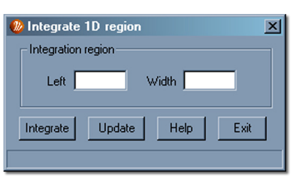

Figure 4.3. Integrate 1D dialog

The "left" and "width" parameters in the Integrate 1D window should update according to the region chosen. If it does not do this automatically, click "Update". Once these parameters are correct click "Integrate". The integration results will be printed to the command line interface (CLI) window.

The next step is to deliberately increase the inhomogeneity of the static field and observe the effects. This can be accomplished by changing the shim settings from the optimal values found during the experiment setup to non-ideal values.

In the pulse and collect experiment window, click “Shims”. The shim dialog will appear (Figure 4.4). The “Saved” values are the values determined during your instrument setup. The “Current” values are the values used during the given experiment.

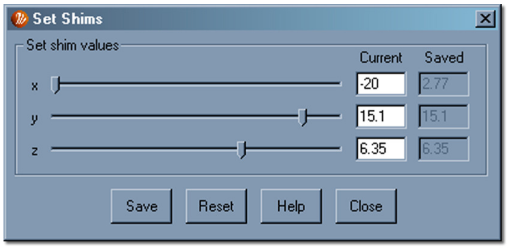

Figure 4.4 The set shims dialog with the x axis shim set to a non-ideal value

Move the x axis slider to a value very different from your ideal saved value. Leaving the shim dialog open, run the pulse and collect experiment. How do the FID and the spectrum change relative to your last measurement? Estimate the peak voltage and decay time constant value of the FID signal. Estimate the width of the peak in the spectrum. Integrate under the sample peak in the spectrum to determine signal amplitude. How do the values compare with the well-shimmed case? Explain your observations using the definition for T_2*.

Close the set shim dialog without saving the current values. Close the pulse and collect dialog.

4.4.4. T_2 and T_2^* Relaxation

In this section of the experiment we will explore the differences between T_2 and T_2*. Recall the relationship between these two relaxation times:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma \Delta B_0$$

T_2 is a consequence of the irreversible de-phasing via spin-spin relaxation, resulting from the random motions of the spins. T_2* combines the irreversible spin-spin relaxation effects (T_2 term) with the reversible magnetic field inhomogeneity de-phasing effects (ΔB_0 term).

Acquire a spin-echo with 4 or 8 averages. Remember to use a pulse and collect FID to select an appropriate echo time and to calculate an appropriate acquisition time. Record the echo amplitude value (printed in the CLI window), that has been obtained by integrating the area under the spectral peak. Repeat the same spin-echo experiment with non-ideal shim values (as done above with pulse and collect). The non-ideal shim values will introduce inhomogeneity into the local Earth’s field. In theory, how will this change T_2? T_2*? In what way does the echo differ? How do the echo amplitudes compare? How do these results compare with the change in signal amplitude obtained for a simple pulse and collect experiment after the same length of time?

Repeat the echo experiment for a number of longer echo times. Record the echo amplitudes as a function of echo time, both in the shimmed and de-shimmed case. Plot the echo amplitudes (both in the shimmed and de-shimmed case) as a function of echo time. What kind of relationship between echo time and echo amplitude do you observe? Is there a difference between the two plots? What relaxation time dependence is there on echo amplitude (T_2 or T_2*)? What relaxation time dependence, T_2 or T_2*, is there on the signal in the FID?

The spin-echo experiment is advantageous because in areas of high magnetic field inhomogeneity it can be used to refocus the signal that decays too quickly to be observed with a pulse and collect experiment. Why?

Run a pulse and collect experiment. Repeat the experiment with non-ideal shim values, repeating the experiment with continuously ‘worse’ shim values until the FID is reduced to just noise. Open the spin-echo experiment and enter the same shim values into its set-shim dialog. Acquire a spin-echo with a short echo time (100 ms) and an appropriate acquisition time. Employ 16 averages. Is any signal observed? What does the spectrum look like? (It may be necessary to observe a wide frequency range of several hundred Hz in order to see anything interesting.) The centre of the echo occurs at a time $2\tau_E$ following the signal excitation (the 90° pulse). What does this result suggest about the relaxation time dependence of the signal magnitude at the centre of the spin-echo?

Close the set-shim dialogs without saving the shim values.

4.4.5. T_2 Measurement

T_2 is measured using a succession of spin-echo experiments with incrementally longer echo times. The plot of echo amplitude as a function of echo time will be an exponential decay with a characteristic decay time constant, T_2. That is, the echo amplitude will be described by:

$$E(\tau_E) = E_0 \exp\left(-2\tau_E / T_2\right) \quad [4.5]$$

where E is the amplitude of an echo acquired with an echo time, τ_E, and E_0 is the echo amplitude in the absence of a T_2 decay. The factor of two appears in the exponential because the centre of the echo occurs at a time of $2\tau_E$ after the 90° excitation pulse.

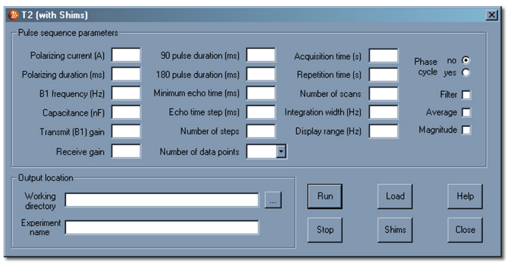

Figure 4.5 T_2 experiment dialog

Open the T_2 experiment from the EFNMR menu. This macro will repeat the spin-echo experiment for an array of echo times. Sampling will commence at the centre of the echo, so the full echo will not be observed. The output of the macro will be the echo amplitudes at each echo time. The echo amplitude is determined by integrating the sample peak in the spectrum. The integration interval is defined in the T_2 dialog. Observe a spectrum from the water sample and choose an appropriate narrow frequency range around the sample peak for this integration.

To accurately measure T_2, using short echo times on the order of 50 ms, it is necessary to purposely disrupt the homogeneity of the Earth's magnetic field such that the FID decays quickly. Why do you think this is necessary? This is accomplished, as above, by de-shimming.

The T_2 for a bulk water sample is on the order of 2 s. Choose an array of echo times for the T_2 experiment accordingly. 50 ms is the shortest echo time that should be employed. What limits the minimum echo time? What is the longest echo time that should be employed to accurately fit the exponential T_2 decay if the T_2 of the sample is 2 s?

Run the experiment. The echo amplitude data is printed to the CLI window and is also plotted in the 1D plot window. The data in the 1D plot window is fitted to equation 4.1 and a value for T_2 is reported in the plot title. If you wish to independently fit the data, copy the output echo amplitude data from the CLI into a spreadsheet program with plotting and fitting capabilities. Plot the echo amplitude *vs*. twice the echo time and fit the echo data to the exponential function (equation 4.1) in order to determine a value for T_2.

4.5. Further Questions

How would you measure the T_2* of a sample?

How is the spin-spin relaxation time, T_2, of a sample used to advantage in Magnetic Resonance Imaging (MRI)?

4.6. Appendix for the Instructor

In this experiment, spin-echoes are used to demonstrate the difference between T_2 and T_2* relaxation times and are also used to measure T_2. The difference between T_2 and T_2* can be seen in the following relation:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma\Delta B_0$$

T_2* is reduced by the presence of magnetic field inhomogeneities, ΔB_0. This is demonstrated in this experiment by de-shimming, i.e. changing the shim values away from the ideal values found during the setup of the instrument. This will disrupt the homogeneity of the local Earth's magnetic field and thus reduce T_2* but have no effect on T_2.

The FID signal from a pulse and collect experiment decays with the T_2* time constant. This is because the magnetic field inhomogeneities across the sample will cause the spins to precess at slightly different resonance frequencies. This spread of frequencies results in a loss of phase coherence and hence a decrease in the observed signal. The greater the inhomogeneity, the more phase coherence, and hence signal, will be lost and so the shorter the decay constant, T_2*.

<u>FID acquired in the presence of a inhomogeneous field</u>: the student should observe that the FID decays more rapidly and the observed peak amplitude of the FID and signal amplitude obtained from integrating the spectrum, will decrease dramatically from that observed in the homogeneous field case. The decrease in the peak amplitude of the FID is a consequence of the delay between excitation and acquisition. During this delay signal is lost due to the T_2* relaxation. In addition, the width of the peak in the spectrum will broaden because of the more rapid decay of the FID signal.

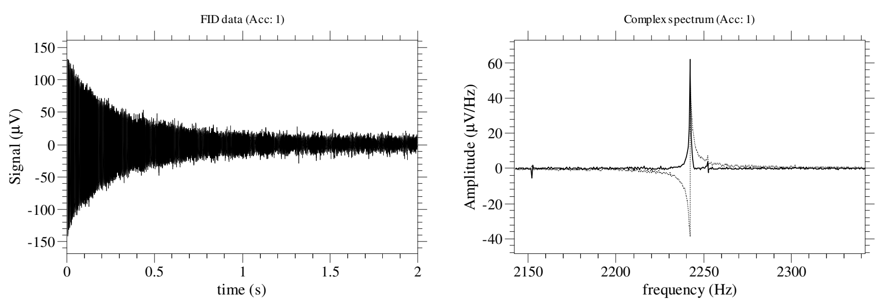

Figure 4.6 An example of an FID and spectrum acquired in the
a field with good homogeneity.

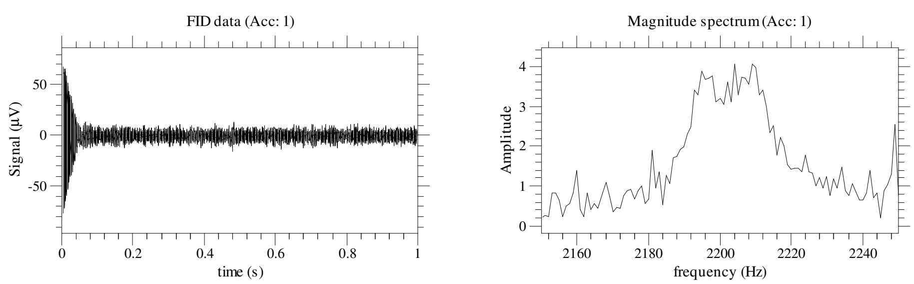

Figure 4.7 An example of a very short FID signal, caused by significant magnetic field inhomogeneity, and the corresponding broad peak in the NMR spectrum.

<u>Spin-echo</u>: the spin-echo amplitude is dependent on T_2, not T_2* because the de-phasing caused by the magnetic field inhomogeneities is reversed by the spin-echo pulse sequence. Therefore in the de-shimmed case the student should observe that the sides of the echo decay more rapidly (this is determined by T_2*) but that the echo amplitude (in the time domain) and the integral under the peak (in the frequency domain) is not changed significantly.

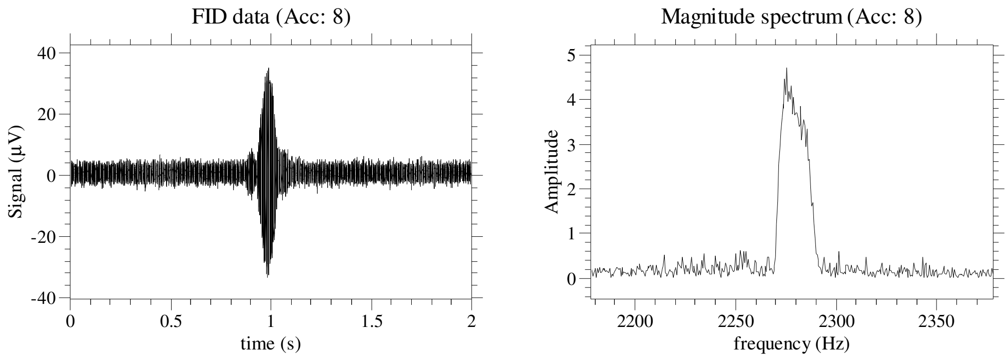

Figure 4.8 A spin-echo signal acquired in a highly inhomogeneous field.

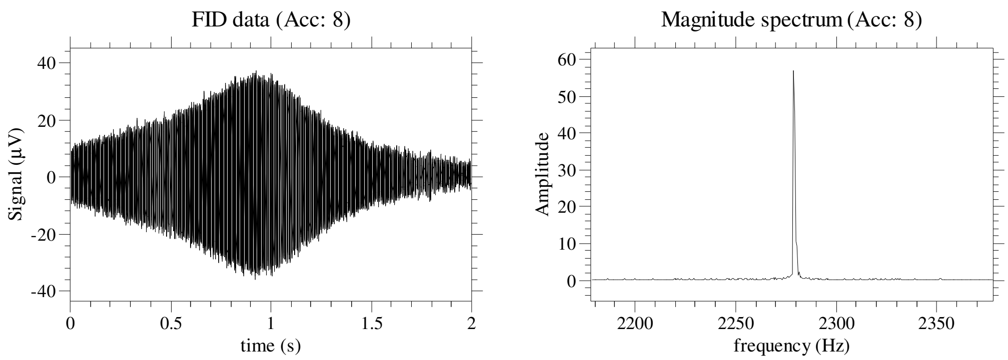

Figure 4.9 A spin-echo signal acquired in the presence of a reasonably homogeneous field.

At longer echo times the echo amplitude should decrease in the same manner for experiments in the shimmed and de-shimmed case because the decay of the echo centre is dependent on T_2, which does not change in the presence of magnetic field inhomogeneity.

It is likely that the students will not observe perfect results because of the non-ideal nature of the 180° pulse. If this pulse is not exactly 180° then the refocusing of dephasing spins due to inhomogeneities in the field is not complete and so the echo amplitude will still have a small dependence on ΔB_0. Therefore there will be some change observed between the experiments in the shimmed and de-shimmed cases. Regardless, the difference between the effect of de-shimming on an FID from the pulse and collect experiment and on the spin-echo signal should be very marked and thus the student results should demonstrate the utility of the spin-echo technique.

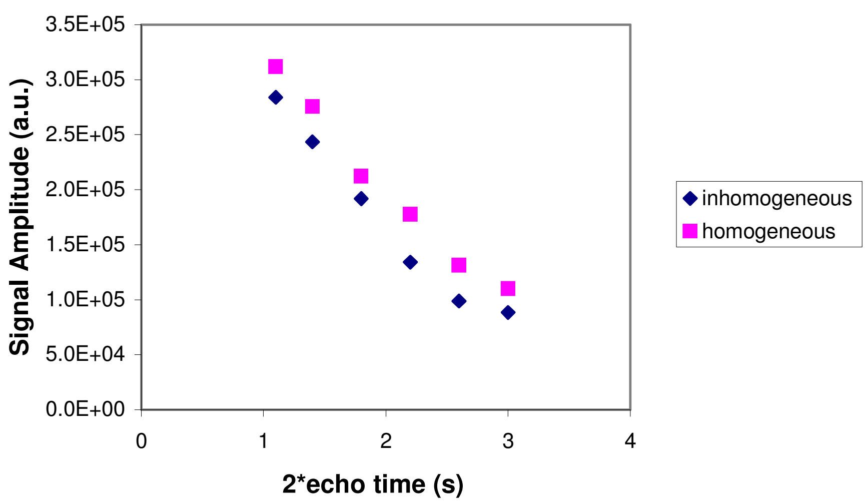

Figure 4.10 The amplitude of the spin-echo over a range of echo times acquired in a homogeneous and an inhomogeneous region, respectively.

Spin-echo T_2 Measurement: The minimum echo time is limited by the ring-down of the coil. The maximum echo time employed to accurately measure T_2 should be several times T_2. For example with a T_2 of 2 s, the maximum echo time should ideally be around 6 s to fully capture the T_2 decay. However, a much shorter maximum echo time is often sufficient to capture the T_2 of the decay.

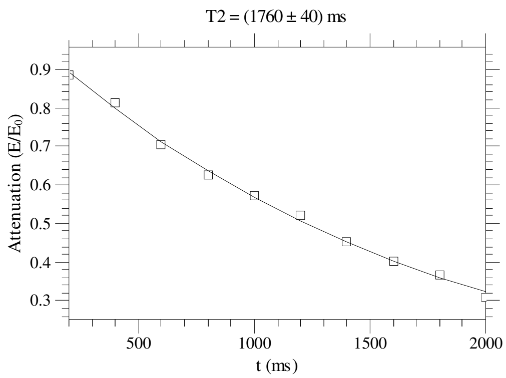

Figure 4.11 Typical results for a measurement of the T_2 of a tap water sample. These results were obtained in de-shimmed conditions.

It is often necessary to purposely disrupt the homogeneity of the Earth's magnetic field in order to accurately measure T_2 because, following the 90° pulse, the excited magnetisation will decay according to T_2*. For short echo times, it is possible that this signal will not decay fully before the 180° pulse. Additionally, if the 180° is non-ideal then it may act as a partial excitation pulse and a partial re-focusing pulse. Both the signal from the 90° pulse and any non-ideal behaviour of the 180° pulse will interfere with the T_2 measurement. If the field homogeneity is purposely "spoiled" via de-shimming, then these signals decay rapidly and do not interfere with the echo formed after the 180° pulse.