Bayesian Data-Analysis Toolbox
Release 4.23, Manual Version 3

G. Larry Bretthorst
Biomedical MR Laboratory
Washington University School Of Medicine,
Campus Box 8227
Room 2313, East Bldg.,
4525 Scott Ave.
St. Louis MO 63110
http://bayes.wustl.edu
Email: gbretthorst@wustl.edu

September 18, 2018

Chapter 14

Magnetization Transfer

The Magnetization transfer package analyzes two site magnetization exchange data. This data is obtained from a peak pick, a Bayes Analyze file or it can be manually entered and loaded as an Ascii file. The Ascii data used in this package are generated from an Fid. The Fid data should be an arrayed inversion recovery data set. If we call the two sites that are exchanging magnetization Site A, and Site B, then the data should be in inversion recover data set where Site A was inverted. You should also have a data set where Site B was inverted. Finally, you can also invert both sites and that data may also be used. Preferably, you should array these Fid so as to obtain as many data values as possible on each recovery curve, the more data you have the more precise you parameter estimates will be. Note, that while it is not recommended, a single inversion recover data set can be used and you will be able to get exchange rates. However, because of the limited about of data, they will probably be highly uncertain. The interface to this package is shown in Fig. 14.1. To use this package, you must do the following:

Select the Magnetization Transfer package from the Package menu.

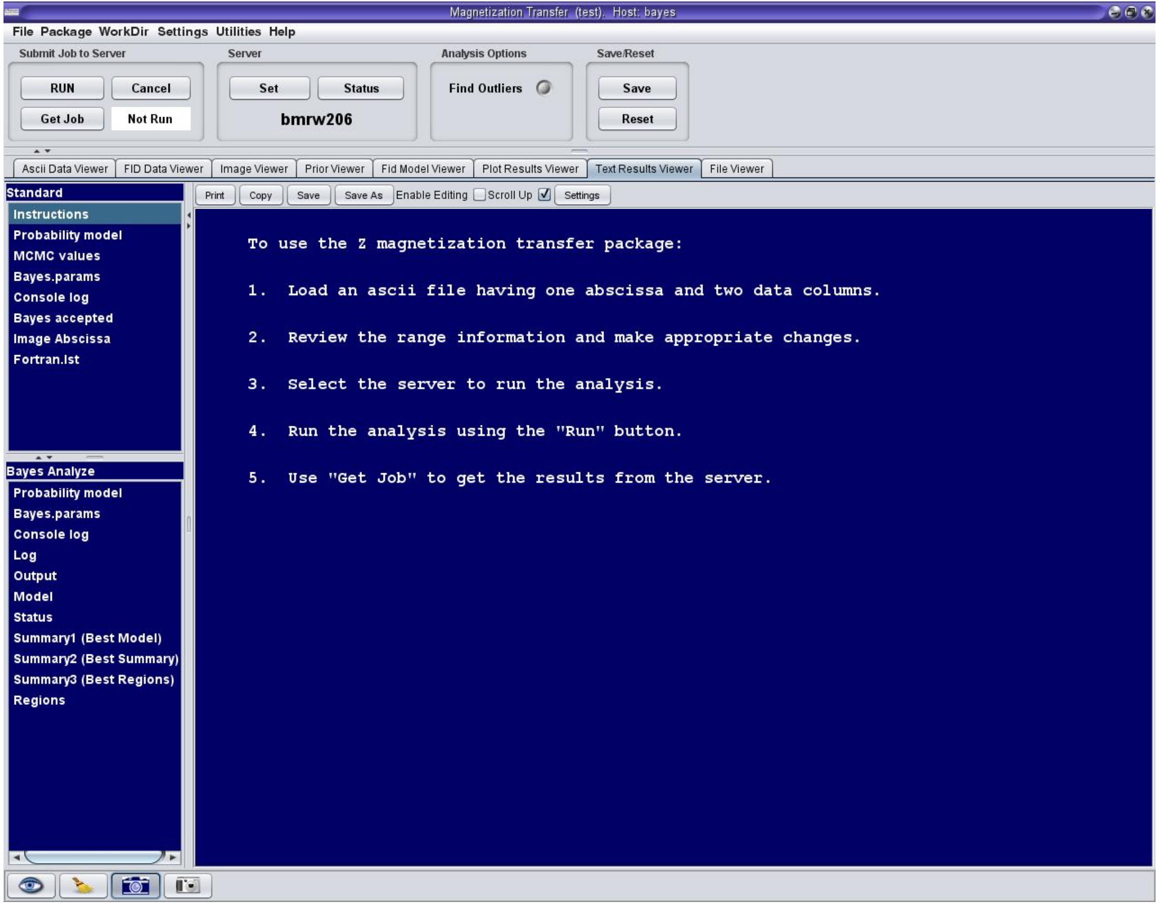
Load at lease one and preferably two three column Ascii data sets using the Files menu. The three columns are the abscissa value, and the amplitude or peak value of the Site A and B magnetization. Additionally, you can load an arrayed Fid and then use a double cursor to mark the center of the two exchanging peaks and use the "Get Peak" button on the bottom right of the Fid viewer. When a data set has been successfully loaded a plot contain the two sites is displayed in the Ascii Data viewer. For Fids, to load a second peak pick or Bayes Analyze file, simply load a second Fid and either load a peak pick or a Bayes Analyze file. Finally, if you have analyzed this Fid using Bayes Analyze you can load the resonance amplitude from the Bayes Analyze files using the "Files/Load Bayes Analyze" menu.

Check the Analysis Options/Find Outliers box if you suspect outliers are present in the data.

Normally the prior probabilities for the parameters would normally have to be reviewed here. However, the calculations are done using a variable transformation, sum and difference variables and this change of variables makes determining prior ranges so easy that the package does it automatically.

Select the server that is to process the analysis.

Figure 14.1: The Magnetization Transfer Package Interface



```
To use the Z magnetization transfer package:

1.  Load an ascii file having one abscissa and two data columns.

2.  Review the range information and make appropriate changes.

3.  Select the server to run the analysis.

4.  Run the analysis using the "Run" button.

5.  Use "Get Job" to get the results from the server.
```

Figure 14.1: The magnetization transfer packages analyzes one or more data set using the equations governing two site magnetization exchange. The inferred parameters are the two exchange rates and the two relaxation rates. For more on the actual calculations and the widgets see the text.

Check the status of the selected server to determine if the server is busy, change to another server if the selected server is busy.

Run the the analysis on the selected server by activating the Run button.

Get the the results of the analysis by activating the Get Job button. If the analysis is running, this button will return the Accepted report containing the status of the current run. Otherwise, it will fetch and display the results from the current analysis.

14.1 The Bayesian Calculation

The two site magnetization transfer package solves problems involving magnetization transfer. If we designate the two sites as "a" and "b" respectively then the magnetization transfer model of the "a" site is related to the data by

$$d_a(t_i) = M_a(t_i) + \text{error} \tag{14.1}$$

and similarly for the "b" site,

$$d_b(t_i) = M_b(t_i) + \text{error} \tag{14.2}$$

where $M_a(t)$ and $M_b(t)$ are the solution to the Bloch-McConnell equations, and "error" represents noise in the data and should not be taken to mean that this noise is the same in both data sets. McConnell's modification to the Bloch equation is given by

$$\frac{dM_a(t)}{dt} = -R_{1a}[M_a(t) - M_a(\infty)] - K_{ab}M_a(t) + K_{ba}M_b(t) \tag{14.3}$$

$$\frac{dM_b(t)}{dt} = -R_{1b}[M_b(t) - M_b(\infty)] - K_{ba}M_b(t) + K_{ab}M_a(t) \tag{14.4}$$

where R_{1a} and R_{1b} are the relaxation rates for the "a" and "b" sites, K_{ba} is the rate at which magnetization goes from the "b" to the "a" site. Similarly K_{ab} is the rate at which magnetization exchanges from the "a" to the "b" site.

These equations are coupled linear first order differential equations and their bi-exponential solution is given by

$$M_a(t) = H(t)M_a(0) + G(t)M_b(0) + \left[1 - H(t) - G(t)\frac{K_{ab}}{K_{ba}}\right] M_a(\infty) \tag{14.5}$$

$$M_b(t) = I(t)M_b(0) - J(t)M_a(0) + \left[J(t) + [1 - I(t)]\frac{K_{ba}}{K_{ba}}\right] M_a(\infty) \tag{14.6}$$

where $M_a(\infty)$ is the equilibrium magnetization for the "a" site, and $M_a(0)$ and $M_b(0)$ are the initial magnetization for the "a" and "b" sites. The functions $G(t)$, $H(t)$, $I(t)$ and $J(t)$ are defined as

$$G(t) = \frac{\exp\{\alpha_1 t\} - \exp\{\alpha_2 t\}}{U - V}, \tag{14.7}$$

$$H(t) = \frac{U\exp\{\alpha_2 t\} - V\exp\{\alpha_1 t\}}{U - V}, \tag{14.8}$$

$$I(t) = \frac{U\exp\{\alpha_1 t\} - V\exp\{\alpha_2 t\}}{U - V}, \tag{14.9}$$

$$J(t) = UVG(t), \tag{14.10}$$

with

$$U = \frac{\alpha_1 + K_{ab} + R_{1a}}{K_{ba}}, \tag{14.11}$$

$$V = \frac{\alpha_2 + K_{ab} + R_{1a}}{K_{ba}}. \tag{14.12}$$

The observed decay rates α_1 and α_2 are given by

$$\alpha_{1,2} = -\frac{R_{1a} + R_{1b} + K_{ab} + K_{ba}}{2} \pm \frac{1}{2}\sqrt{(R_{1a} - R_{1b} - K_{ab} - K_{ba})^2 + 4K_{ab}K_{ba}} \tag{14.13}$$

where α_1 takes the plus and α_2 the minus.

The four parameters of interest are the two exchange rates K_{ab} and K_{ba} and the two relaxation rates R_{1a} and R_{1b}. In addition there are three parameters per "a" and "b" site that must be included, two initial conditions magnetizations, $M_a(0)$ and $M_b(0)$ and one equilibrium magnetization $M_a(\infty)$. The equilibrium condition,

$$M_b(\infty) = M_a(\infty)\frac{K_{ab}}{K_{ba}} \tag{14.14}$$

was used to eliminate $M_b(\infty)$.

Before we start the process of computing the posterior probability for the parameters of interest, K_{ab}, K_{ba}, R_{1a} and R_{1b}, we are going to rewrite the model equations and the data into a form that is more convenient for the upcoming analytic calculation. First we are going to define a single data set D with data item $d(t_i)$ that is the "a" site data followed by the "b" site data:

$$d(t_i) = \begin{cases} d_a(t_i) & \text{if } 1 \le i \le N \\ d_b(t_j) & \text{if } 1 \le j \le N \text{ with } j \equiv i - N \end{cases} \tag{14.15}$$

where the index i ranges from 1 up to $2N$. This definition is roughly like defining a complex data set with the "a" site being the real data and the "b" site being the imaginary data. Next we will rewrite Eqs. (14.1 and 14.2) into a single equation:

$$d(t_i) = \sum_{k=1}^{3} M_k \mathcal{H}_k(t_i) + \text{error} \tag{14.16}$$

where $M_1 \equiv M_a(0)$, $M_2 \equiv M_b(0)$ and $M_3 \equiv M_a(\infty)$. Finally, the three functions $\mathcal{H}_1(t_i)$, $\mathcal{H}_2(t_i)$ and $\mathcal{H}_3(t_i)$ are defined as

$$\mathcal{H}_1(t_i) = \begin{cases} H(t_i) & \text{if } 1 \le i \le N \\ -J(t_j) & \text{if } 1 \le j \le N \text{ with } j \equiv i - N \end{cases}, \tag{14.17}$$

$$\mathcal{H}_2(t_i) = \begin{cases} G(t_i) & \text{if } 1 \le i \le N \\ I(t_j) & \text{if } 1 \le j \le N \text{ with } j \equiv i - N \end{cases} \tag{14.18}$$

and

$$\mathcal{H}_3(t_i) = \begin{cases} (1 - H(t_i) - G(t_i)K_{ab}/K_{ba}) & \text{if } 1 \le i \le N \\ (J(t_j) + [1 - I(t_j)]K_{ab}/K_{ba}) & \text{if } 1 \le j \le N \text{ with } j \equiv i - N \end{cases}. \tag{14.19}$$

In magnetization transfer problems it is often possible to take multiple independent measurements of the exchanging spins. For example one can invert the "a" site and then watch the effect of the relaxation on the "b" site spins. Similarly, one could invert the "b" site and then even invert both sites simultaneously. Consequently, we are going to adopt the notation, $d_j(t_i)$, to designate the ith data item of the jth inversion recovery. Similarly, M_{j1} will the initial "a" site magnetization for the jth inversion recovery. In what follows, it should be understood that different data sets may have different acquisitions times, even though we will not adopt a notation to represent this.

The joint posterior probability for the four parameters of interest is represented symbolically by $P(K_{ab}K_{ba}R_{1a}R_{1b}|DI)$, where D are the amplitudes or peak intensities for the "a" and "b" sites for *all* of the data sets. If we designate the posterior probability for the parameters computed from the jth data set as $P(K_{ab}K_{ba}R_{1a}R_{1b}|D_jI)$ then the posterior probability computed from all of the data is given by

$$P(K_{ab}K_{ba}R_{1a}R_{1b}|DI) = \prod_{j=1}^{m} P(K_{ab}K_{ba}R_{1a}R_{1b}|D_jI). \tag{14.20}$$

The right-hand side of this equation is computed from the joint posterior probability for all of the parameters:

$$P(K_{ab}K_{ba}R_{1a}R_{1b}|D_jI) = \int P(K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma|D_jI)dM_{j1}dM_{j2}dM_{j3}d\sigma \tag{14.21}$$

where the amplitudes and standard deviation for the noise prior probability have been removed by marginalization. To compute the joint posterior probability for all of the parameters, we first factor the integrand using Bayes' theorem:

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma|D_jI) &\propto P(K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma_j|I) \\ &\times P(D_j|K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma_jI). \end{aligned} \tag{14.22}$$

Next the joint prior probability for the parameters, $P(K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma_j|I)$, is factored into a series of independent priors for each of the parameters:

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}M_{j1}M_{j2}M_{j3}\sigma_j|I) &= P(K_{ab}|I)P(K_{ba}|I)P(R_{1a}|I)P(R_{1b}|I) \\ &\times P(M_{j1}|I)P(M_{j2}|I)P(M_{j3}|I)P(\sigma_j|I). \end{aligned} \tag{14.23}$$

Using Eqs. (14.23,14.22,14.21 and 14.20), one obtains,

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}|DI) &= P(K_{ab}|I)P(K_{ba}|I)P(R_{1a}|I)P(R_{1b}|I) \\ &\times \prod_{j=1}^{m}\Bigg[\int dM_{j1}dM_{j2}dM_{j3}d\sigma_j P(\sigma_j|I) \\ &\quad \times P(M_{j1}|I)P(M_{j2}|I)P(M_{j3}|I) \\ &\quad \times P(D_j|K_{ab}K_{ba}R_{1a}R_{1b}M_{J1}M_{j2}M_{j3}\sigma_jI)\Bigg] \end{aligned} \tag{14.24}$$

as the posterior probability for the parameters of interest.

We have now reached the point in the calculation where we must assign numerical values to represent these probabilities. The prior probabilities for the four parameters of interest are assigned as Gaussians that are constructed out of the Low-High ranges that are input on the interface. If x denotes one of the four parameters of interest, then its prior probability is given by

$$P(x|I) \propto \begin{cases} \exp\left\{-\frac{(\mathrm{Mean}-x)^2}{2\mathrm{Sd}^2}\right\} & \text{if Low} \le x \le \text{High} \\ 0 & \text{otherwise} \end{cases} \tag{14.25}$$

where "Low" and "High" appropriate inputs from the interface, "Mean" is the average of the low and high, and "Sd" is set so that the High-Low interval represents a 3 standard deviation interval.

The prior probabilities for the standard deviation of the noise was assigned as a Jeffreys' prior, $1/\sigma_j$. The prior probability for the amplitudes was assigned using a uniform prior probability. Finally, the likelihoods were assigned using a Gaussian of standard deviation σ_j, one obtains

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}|DI) \propto\; & P(K_{ab}|I)P(K_{ba}|I)P(R_{1a}|I)P(R_{1b}|I) \\ & \times \prod_{j=1}^{m}\left[\int dM_{j1}dM_{j2}dM_{j3}\frac{d\sigma_j}{\sigma_j}\left(2\pi\sigma_j^2\right)^{-N}\exp\left\{-\frac{Q_j}{2\sigma_j^2}\right\}\right] \end{aligned} \tag{14.26}$$

where we have left the four prior probabilities for the parameters of interest in their symbolic form, and

$$\begin{aligned} Q_j \;&\equiv\; \sum_{i=1}^{2N}\left[d_j(t_i) - \sum_{\ell=1}^{3}M_{j\ell}\mathcal{H}_j(t_i)\right]^2 \\ &=\; 2N_j(\overline{d^2})_j - 2\sum_{\ell=1}^{3}M_{j\ell}T_{j\ell} + \sum_{k=1}^{3}\sum_{l=1}^{3}(g_{kl})_j M_{jk}M_{jl}. \end{aligned} \tag{14.27}$$

The mean-squared data value, $(\overline{d^2})_j$, for the jth inversion is defined as

$$(\overline{d^2})_j = \frac{1}{2N_j}\sum_{i=1}^{2N_j}d_j(t_i)^2 \equiv \frac{1}{2N_j}\sum_{i=1}^{N_j}d_{aj}(t_i)^2 + d_{bj}(t_i)^2 \tag{14.28}$$

where N_j is the number of complex data values in the jth inversion. The projection of the ℓth model function onto the jth inversion, $T_{j\ell}$, is given by

$$T_{j\ell} = \sum_{i=1}^{2N_j}d_j(t_i)\mathcal{H}_{j\ell}(t_i). \tag{14.29}$$

The matrix $(g_{kl})_j$ is defined by

$$(g_{kl})_j \equiv \sum_{i=1}^{2N_j}\mathcal{H}_{jk}(t_i)\mathcal{H}_{j\ell}(t_i). \tag{14.30}$$

This matrix will depend on the individual inversion if the delay times differ from one inversion to another.

Evaluating the integrals over the amplitudes and standard deviations is straightforward, if not tedious. Evaluating the amplitude integrals one obtains:

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}|DI) \propto\; & P(K_{ab}|I)P(K_{ba}|I)P(R_{1a}|I)P(R_{1b}|I) \\ & \times \prod_{j=1}^{m}\int\frac{d\sigma_j}{\sigma_j}\,|g_{kl}|_j^{-\frac{1}{2}}\left(2\pi\sigma_j^2\right)^{-N+3}\exp\left\{-\frac{2N_j(\overline{d^2})_j - (\overline{h^2})_j}{2\sigma_j^2}\right\} \end{aligned} \tag{14.31}$$

where $|g_{kl}|_j$ is the determinant of the $(g_{jk})_j$ matrix. The sufficient statistic, $(\overline{h^2})_j$, is the total-squared projection of the model onto the data for the jth inversion:

$$(\overline{h^2})_j = \sum_{k=1}^{3} T_{kj}\hat{M}_{kj}. \tag{14.32}$$

The $\hat{M}_{kj}$, are given by the solution to the following linear set of equations:

$$\sum_{k=1}^{3}(g_{lk})_j\hat{M}_{kj} = T_{lj} \qquad (1 \leq l \leq 3). \tag{14.33}$$

The integrals over the standard deviations of the noise prior probabilities may all be transformed into Gamma functions and evaluating such integrals is straightforward, one obtains

$$\begin{aligned} P(K_{ab}K_{ba}R_{1a}R_{1b}|D_aD_bI) \quad &\propto \quad P(K_{ab}|I)P(K_{ba}|I)P(R_{1a}|I)P(R_{1b}|I) \\ &\times \quad \prod_{j=1}^{m}|g_{kl}|_j^{-\frac{1}{2}}\left[2N_j(\overline{d^2})_j - (\overline{h^2})_j\right]^{\frac{3-N_j}{2}} \end{aligned} \tag{14.34}$$

where we have dropped a number of constants that cancel when this distribution is normalized.

Markov chain Monte Carlo with simulated annealing is used to draw samples from the joint posterior probability for K_{ab}, K_{ba}, R_{1a} and R_{1b}, Eq. (14.34). These samples are used to approximate the marginal posterior probability for each of the parameters separately. In addition, the program also uses these samples to form an approximation to the posterior probability for the volume fractions,

$$p_a = \frac{K_{ba}}{K_{ab}+K_{ba}} \quad \text{and} \quad p_b = \frac{K_{ab}}{K_{ab}+K_{ba}}, \tag{14.35}$$

the exchange times,

$$\tau_{ab} = \frac{1}{K_{ab}} \quad \text{and} \quad \tau_{ba} = \frac{1}{K_{ba}}, \tag{14.36}$$

and the relaxation times,

$$T_{1a} = \frac{1}{R_{1a}} \quad \text{and} \quad T_{1b} = \frac{1}{R_{1b}}. \tag{14.37}$$

Note that in each of these calculations involves a change of variables of the form $Y = 1/X$. This change of variables introduces a factor of the form $dY = -dXX^{-2}$ into the posterior. This factor shift the location of the maximum posterior probability between the paired variables. Consequently, the maximum posterior probability estimate for Y is not in general equal to $1/X$.

14.2 Using The Package

The Text outputs files from the Magnetization Transfer packages consist of: “Bayes.prob.model,” “MtZ.mcmc.values,” “Bayes.params,” “Console.log,” “Bayes.accepted” and a “Bayes.Condensed.File.” These output files can be viewed using the Text Viewer or they can be viewed using File Viewer by navigating to the current working directory and then selecting the files. The format of the

Figure 14.2: Magnetization Transfer Package Peak Picking

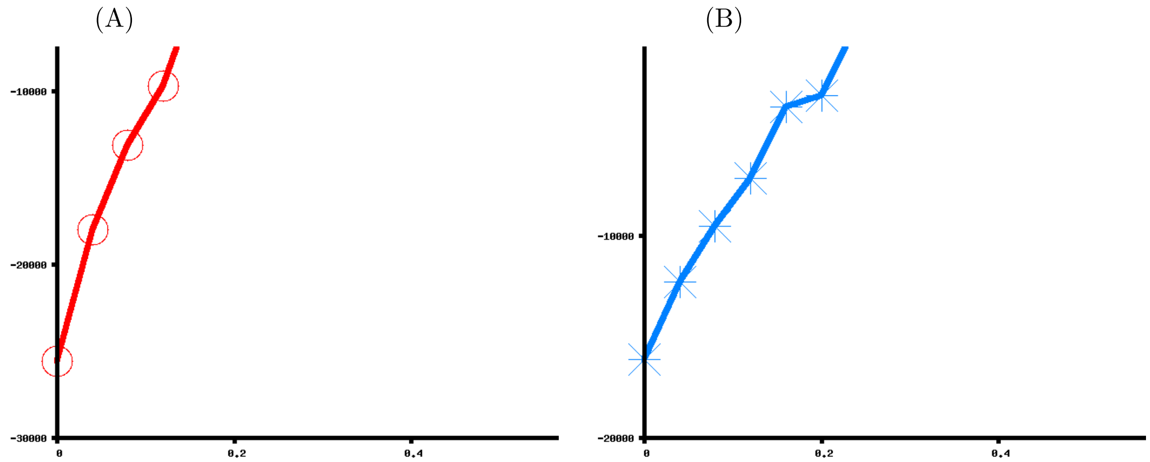


Figure 14.2: The peak intensities of the exchanging sites are analyzed by the magnetization exchange package, consequently, as illustrated here, the data are three column Ascii: a time, and two peak intensities. These peak intensities may be loaded from a peak pick, a Bayes Analyze run, or from an Ascii file. The example shown in this figure is from an peak pick. Panel (A) is the peak intensities when the left-hand peak was inverted and Panel (B) is the peak intensities when the right-hand peak was inverted. The data shown in Panel (A) was generated using a peak pick of the inversion recovey spectrum shown in Figure 14.3.

mcmc.values report is discussed in Appendix D and the other reports are discussed in Chapter ??. Additionally, the "Plot Results Viewer" can be used to view the output probability density functions. In addition to the standard data, model and residual plots there are probability density functions for the decay rate constants, decay times, the amplitudes for each data set for each exponential and finally there are probability density functions for the standard deviation of the noise in each data set.

The data used by this package can be multiple three column Ascii files, see Fig. 14.2 for an example of this data. The data consists of a time axis and the left and right-hand peak intensity from an inversion recover experiment. The data can be loaded in one of three ways: First, a three column Ascii file can be directly loaded using the Files menu; Second, The spectrum of a magnetization transfer inversion recovery Fid can be loaded and the peak amplitudes can be extracted and loaded. Third, the "File/Load Ascii/Bayes Analyze File" button can be used to extract the peak amplitudes from the currently loaded Bayes Analyze files. If Bayes Analyze has not been run on this Fid, you must run it before you can use this option.

Figure 14.3 is the first trace in the spectrum of the inversion recover used to generate the data shown in Fig. 14.2(A). Figure 14.4 is a plot of the spectrum of the two exchanging resonances for each delay time in the inversion recover experiment shown in Fig. 14.3. Note how the left-hand resonances starts inverted and as a function of the delay time it rather quickly recovers. If you examine Fig. 14.4, which is a VnmrJ dssh display of the region around the two exchanging peaks, you can easily see that, initially both peaks have reduced amplitude and as the left-hand peak recovers, both peaks

Figure 14.3: Magnetization Transfer Example Data

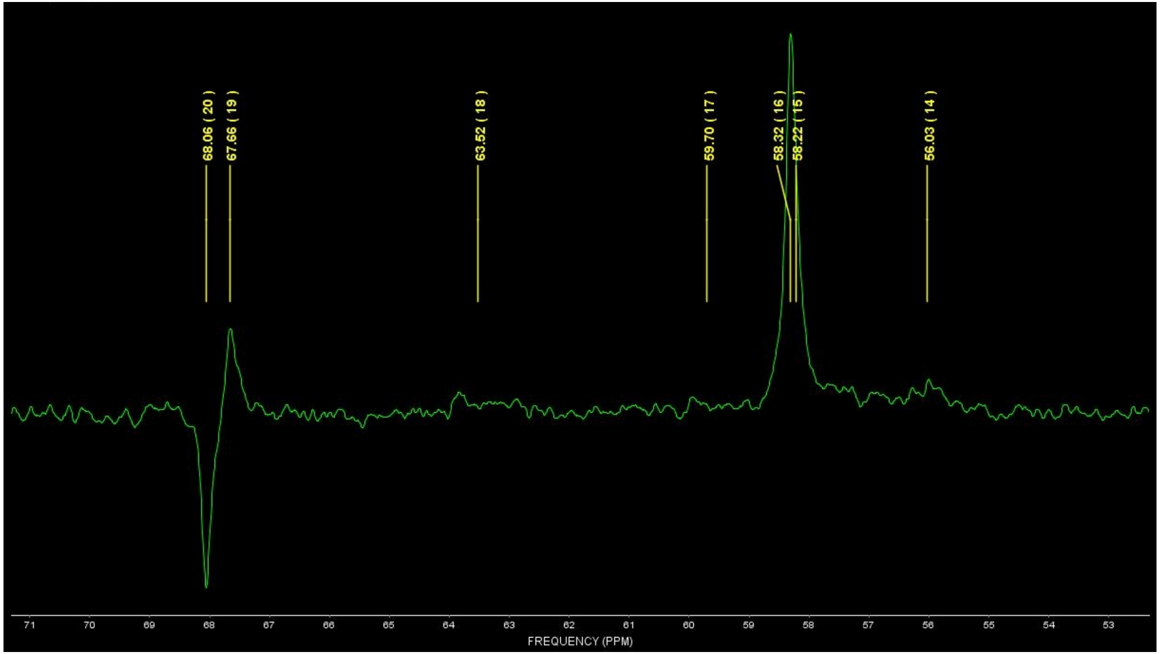


Figure 14.3: The three columns are the abscissa, in this case a delay time, and the amplitudes of the resonances of the A and B Sites. In this spectrum Site A is the resonance near 68PPM, and Site B is near 67.66PPM. To load this data, place a double cursor on each resonance and hit the “Get Peak” button in the lower right. Alternately, If Bayes Analyze has been run on this data, the “File/Load Ascii/Bayes Analyze File” menu can be used to load the resonance amplitudes from the Bayes Analyze files.

Figure 14.4: Magnetization Transfer Example Spectrum

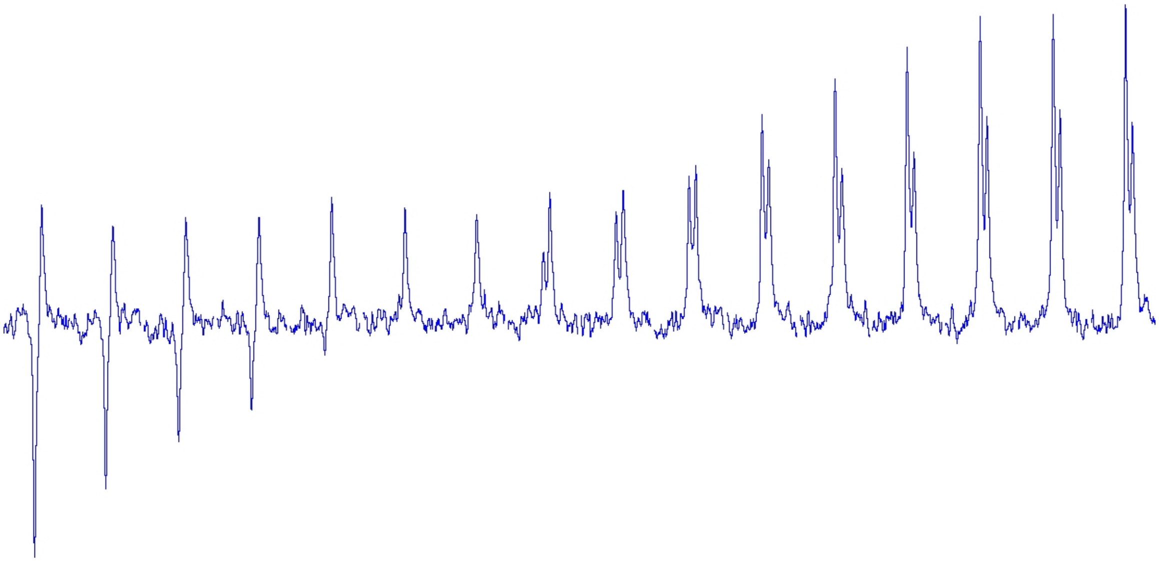


Figure 14.4: These spectra are a typical example of magnetization transfer data. Here the left-hand peak was selectively inverted and allow to recover. The data analyzed by the magnetization transfer package is the peak intensity or amplitude of the two sites exchanging magnetization. These peak intensity may be loaded using the File menu, extracted using a double cursor and the Get Peak button, or Bayes Analyze can be used to estimate the amplitudes, and these amplitudes can be loaded using the File/Ascii File/Bayes Analyze menu.

increase in intensity. In the three column Ascii data shown in Fig 14.2(A) the left-hand peak shown in Fig 14.3 was selectively inverted and then allowed to relax back to equilibrium. It is the peak intensities of the two resonances exchanging magnetization that are analyzed by the magnetization package.

Bibliography

[1] Rev. Thomas Bayes (1763), "An Essay Toward Solving a Problem in the Doctrine of Chances," *Philos. Trans. R. Soc. London*, **53,** pp. 370-418; reprinted in *Biometrika*, **45**, pp. 293-315 (1958), and *Facsimiles of Two Papers by Bayes,* with commentary by W. Edwards Deming, New York, Hafner, 1963.

[2] G. Larry Bretthorst (1988), "Bayesian Spectrum Analysis and Parameter Estimation," in *Lecture Notes in Statistics,* **48**, J. Berger, S. Fienberg, J. Gani, K. Krickenberg, and B. Singer (eds), Springer-Verlag, New York, New York.

[3] G. Larry Bretthorst (1990), "An Introduction to Parameter Estimation Using Bayesian Probability Theory," in *Maximum Entropy and Bayesian Methods,* Dartmouth College 1989, P. Fougère *ed.,* pp. 53-79, Kluwer Academic Publishers, Dordrecht the Netherlands.

[4] G. Larry Bretthorst (1990), "Bayesian Analysis I. Parameter Estimation Using Quadrature NMR Models" *J. Magn. Reson.*, **88**, pp. 533-551.

[5] G. Larry Bretthorst (1990), "Bayesian Analysis II. Signal Detection And Model Selection" *J. Magn. Reson.*, **88**, pp. 552-570.

[6] G. Larry Bretthorst (1990), "Bayesian Analysis III. Examples Relevant to NMR" *J. Magn. Reson.*, **88**, pp. 571-595.

[7] G. Larry Bretthorst (1991), "Bayesian Analysis. IV. Noise and Computing Time Considerations," *J. Magn. Reson.*, **93**, pp. 369-394.

[8] G. Larry Bretthorst (1992), "Bayesian Analysis. V. Amplitude Estimation for Multiple Well-Separated Sinusoids," *J. Magn. Reson.*, **98**, pp. 501-523.

[9] G. Larry Bretthorst (1992), "Estimating The Ratio Of Two Amplitudes In Nuclear Magnetic Resonance Data," in *Maximum Entropy and Bayesian Methods,* C. R. Smith *et al.* (eds.), pp. 67-77, Kluwer Academic Publishers, the Netherlands.

[10] G. Larry Bretthorst (1993), "On The Difference In Means," in Physics & Probability Essays in honor of Edwin T. Jaynes, W. T. Grandy and P. W. Milonni (eds.), pp. 177-194, Cambridge University Press, England.

[11] G. Larry Bretthorst (1996), "An Introduction To Model Selection Using Bayesian Probability Theory," in *Maximum Entropy and Bayesian Methods*, G. R. Heidbreder, ed., pp. 1-42, Kluwer Academic Publishers, Printed in the Netherlands.

[12] G. Larry Bretthorst (1999), "The Near-Irrelevance of Sampling Frequency Distributions," in *Maximum Entropy and Bayesian Methods,* W. von der Linden *et al.* (eds.), pp. 21-46, Kluwer Academic Publishers, the Netherlands.

[13] G. Larry Bretthorst (2001), "Nonuniform Sampling: Bandwidth and Aliasing," in *Maximum Entropy and Bayesian Methods in Science and Engineering,* Joshua Rychert, Gary Erickson and C. Ray Smith *eds.*, pp. 1-28, American Institute of Physics, USA.

[14] G. Larry Bretthorst, Christopher D. Kroenke, and Jeffrey J. Neil (2004), "Characterizing Water Diffusion In Fixed Baboon Brain," in Bayesian Inference And Maximum Entropy Methods In Science And Engineering, Rainer Fischer, Roland Preuss and Udo von Toussaint *eds.*, AIP conference Proceedings, **735**, pp. 3-15.

[15] G. Larry Bretthorst, William C. Hutton, Joel R. Garbow, and Joseph J.H. Ackerman (2005), "Exponential parameter estimation (in NMR) using Bayesian probability theory," *Concepts in Magnetic Resonance*, 27A, Issue 2, pp. 55-63.

[16] G. Larry Bretthorst, William C. Hutton, Joel R. Garbow, and Joseph J. H. Ackerman (2005), "Exponential model selection (in NMR) using Bayesian probability theory," *Concepts in Magnetic Resonance*, 27A, Issue 2, pp. 64-72.

[17] G. Larry Bretthorst, William C. Hutton, Joel R. Garbow, and Joseph J.H. Ackerman (2005), "How accurately can parameters from exponential models be estimated? A Bayesian view," *Concepts in Magnetic Resonance*, 27A, Issue 2, pp. 73-83.

[18] G. Larry Bretthorst, W. C. Hutton, J. R. Garbow, and Joseph J. H. Ackerman (2008), "High Dynamic Range MRS Time-Domain Signal Analysis," *Magn. Reson. in Med.*, **62**, pp. 1026-1035.

[19] V. Chandramouli, K. Ekberg, W. C. Schumann, S. C. Kalhan, J. Wahren, and B. R. Landau (1997), "Quantifying gluconeogenesis during fasting," *American Journal of Physiology*, **273**, pp. H1209-H1215.

[20] R. T. Cox (1961), "The Algebra of Probable Inference," Johns Hopkins Univ. Press, Baltimore.

[21] André d'Avignon, G. Larry Bretthorst, Marilyn Emerson Holtzer, and Alfred Holtzer (1998), "Site-Specific Thermodynamics and Kinetics of a Coiled-Coil Transition by Spin Inversion Transfer NMR," *Biophysical Journal*, **74**, pp. 3190-3197.

[22] André d'Avignon, G. Larry Bretthorst, Marilyn Emerson Holtzer, and Alfred Holtzer (1999), "Thermodynamics and Kinetics of a Folded-Folded Transition at Valine-9 of a GCN4-Like Leucine Zipper," *Biophysical Journal*, **76**, pp. 2752-2759.

[23] David Freedman, and Persi Diaconis (1981), "On the histogram as a density estimator: L_2 theory," *Zeitschrift für Wahrscheinlichkeitstheorie und verwandte Gebiete*, **57**, 4, pp. 453-476.

[24] W. R. Gilks, S. Richardson, and D. J. Spiegelhalter (1996), "Markov Chain Monte Carlo in Practice," Chapman & Hall, London.

[25] Paul M. Goggans, and Ying Chi (2004), "Using Thermodynamic Integration to Calculate the Posterior Probability in Bayesian Model Selection Problems," in *Bayesian Inference and Maximum Entropy Methods in Science and Engineering: 23rd International Workshop*, **707**, pp. 59-66.

[26] Marilyn Emerson Holtzer, G. Larry Bretthorst, D. André d'Avignon, Ruth Hogue Angelette, Lisa Mints, and Alfred Holtzer (2001), "Temperature Dependence of the Folding and Unfolding Kinetics of the GCN4 Leucine Lipper via 13C alpha-NMR," *Biophysical Journal*, **80**, pp. 939-951.

[27] E. T. Jaynes (1968), "Prior Probabilities," *IEEE Transactions on Systems Science and Cybernetics*, SSC-4, pp. 227-241; reprinted in [30].

[28] E. T. Jaynes (1978), "Where Do We Stand On Maximum Entropy?" in *The Maximum Entropy Formalism*, R. D. Levine and M. Tribus *Eds.*, pp. 15-118, Cambridge: MIT Press, Reprinted in [30].

[29] E. T. Jaynes (1980), "Marginalization and Prior Probabilities," in *Bayesian Analysis in Econometrics and Statistics*, A. Zellner *ed.,* North-Holland Publishing Company, Amsterdam; reprinted in [30].

[30] E. T. Jaynes (1983), "Papers on Probability, Statistics and Statistical Physics," a reprint collection, D. Reidel, Dordrecht the Netherlands; second edition Kluwer Academic Publishers, Dordrecht the Netherlands, 1989.

[31] E. T. Jaynes (1957), "How Does the Brain do Plausible Reasoning?" unpublished Stanford University Microwave Laboratory Report No. 421; reprinted in *Maximum-Entropy and Bayesian Methods in Science and Engineering* **1,** pp. 1-24, G. J. Erickson and C. R. Smith *Eds.,* 1988.

[32] E. T. Jaynes (2003), "Probability Theory—The Logic of Science," edited by G. Larry Bretthorst, Cambridge University Press, Cambridge UK.

[33] Sir Harold Jeffreys (1939), "Theory of Probability," Oxford Univ. Press, London; Later editions, 1948, 1961.

[34] John G. Jones, Michael A. Solomon, Suzanne M. Cole, A. Dean Sherry, and Craig R. Malloy (2001) "An integrated ^{2}H and ^{13}C NMR study of gluconeogenesis and TCA cycle flux in humans," *American Journal of Physiology, Endocrinology, and Metabolism,* **281,** pp. H848-H856.

[35] John Kotyk, N. G. Hoffman, W. C. Hutton, G. Larry Bretthorst, and J. J. H. Ackerman (1992), "Comparison of Fourier and Bayesian Analysis of NMR Signals. I. Well-Separated Resonances (The Single-Frequency Case)," *J. Magn. Reson.*, **98**, pp. 483–500.

[36] Pierre Simon Laplace (1814), "A Philosophical Essay on Probabilities," John Wiley & Sons, London, Chapman & Hall, Limited 1902. Translated from the 6th edition by F. W. Truscott and F. L. Emory.

[37] N. Lartillot, and H. Philippe (2006), "Computing Bayes Factors Using Thermodynamic Integration," *Systematic Biology*, **55** (2), pp. 195-207.

[38] D. Le Bihan, and E. Breton (1985), "Imagerie de diffusion in-vivo par rsonance," Comptes rendus de l'Acadmie des Sciences (Paris), **301** (15), pp. 1109-1112.

[39] N. R. Lomb (1976), "Least-Squares Frequency Analysis of Unevenly Spaced Data," *Astrophysical and Space Science*, **39**, pp. 447-462.

[40] T. J. Loredo (1990), "From Laplace To SN 1987A: Bayesian Inference In Astrophysics," in *Maximum Entropy and Bayesian Methods,* P. F. Fougere (ed), Kluwer Academic Publishers, Dordrecht, The Netherlands.

[41] Craig R. Malloy, A. Dean Sherry, and Mark Jeffrey (1988), "Evaluation of Carbon Flux and Substrate Selection through Alternate Pathways Involving the Citric Acid Cycle of the Heart by 13C NMR Spectroscopy," *Journal of Biological Chemistry*, **263** (15), pp. 6964-6971.

[42] Craig R. Malloy, Dean Sherry, and Mark Jeffrey (1990), "Analysis of tricarboxylic acid cycle of the heart using ^{13}C isotope isomers," *American Journal of Physiology*, **259**, pp. H987-H995.

[43] Lawrence R. Mead and Nikos Papanicolaou, "Maximum entropy in the problem of moments," *J. Math. Phys.* **25**, 2404–2417 (1984).

[44] K. Merboldt, Wolfgang Hanicke, and Jens Frahm (1969), "Self-diffusion NMR imaging using stimulated echoes," Journal of Magnetic Resonance, **64** (3), pp. 479-486.

[45] Nicholas Metropolis, Arianna W. Rosenbluth, Marshall N. Rosenbluth, Augusta H. Teller, and Edward Teller (1953), "Equation of State Calculations by Fast Computing Machines," Journal of Chemical Physics. The previous link is to the Americain Institute of Physics and if you do not have access to Science Sitations you many not be able to retrieve this paper.

[46] Radford M. Neal (1993), "Probabilistic Inference Using Markov Chain Monte Carlo Methods," technical report CRG-TR-93-1, Dept. of Computer Science, University of Toronto.

[47] Jeffrey J. Neil, and G. Larry Bretthorst (1993), "On the Use of Bayesian Probability Theory for Analysis of Exponential Decay Data: An Example Taken from Intravoxel Incoherent Motion Experiments," *Magn. Reson. in Med.*, **29**, pp. 642–647.

[48] H. Nyquist (1924), "Certain Factors Affecting Telegraph Speed," *Bell System Technical Journal*, **3**, pp. 324-346.

[49] H. Nyquist (1928), "Certain Topics in Telegraph Transmission Theory," *Transactions AIEE*, **3**, pp. 617-644.

[50] William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery (1992), "Numerical Recipes The Art of Scientific Computing Second Edition," Cambridge University Press, Cambridge UK.

[51] Emanuel Parzen (1962), "On Estimation of a Probability Density Function and Mode," *Annals of Mathematical Statistics* **33**, 1065–1076

[52] Karl Pearson (1895), "Contributions to the Mathematical Theory of Evolution. II. Skew Variation in Homogeneous Material," *Phil. Trans. R. Soc. A* **186**, 343–326.

[53] Murray Rosenblatt, "Remarks on Some Nonparametric Estimates of a Density Function," *Annals of Mathematical Statistics* **27**, 832–837 (1956).

[54] Jeffery D. Scargle (1981), "Studies in Astronomical Time Series Analysis I. Random Process In The Time Domain," *Astrophysical Journal Supplement Series*, **45**, pp. 1-71.

[55] Jeffery D. Scargle (1982), "Studies in Astronomical Time Series Analysis II. Statistical Aspects of Spectral Analysis of Unevenly Sampled Data," *Astrophysical Journal*, **263**, pp. 835-853.

[56] Jeffery D. Scargle (1989), "Studies in Astronomical Time Series Analysis. III. Fourier Transforms, Autocorrelation Functions, and Cross-correlation Functions of Unevenly Spaced Data," *Astrophysical Journal*, **343**, pp. 874-887.

[57] Arthur Schuster (1905), "The Periodogram and its Optical Analogy," *Proceedings of the Royal Society of London*, **77**, p. 136-140.

[58] Claude E. Shannon (1948), "A Mathematical Theory of Communication," *Bell Syst. Tech. J.*, **27**, pp. 379-423.

[59] John E. Shore, and Rodney W. Johnson (1981), "Properties of cross-entropy minimization," *IEEE Trans. on Information Theory*, **IT-27,** No. 4, pp. 472-482.

[60] John E. Shore and Rodney W. Johnson (1980), "Axiomatic derivation of the principle of maximum entropy and the principle of minimum cross-entropy," *IEEE Trans. on Information Theory*, **IT-26** (1), pp. 26-37.

[61] Devinderjit Sivia, and John Skilling (2006), "Data Analysis: A Bayesian Tutorial," Oxford University Press, USA.

[62] Edward O. Stejskal and Tanner, J. E. (1965), "Spin Diffusion Measurements: Spin Echoes in the Presence of a Time-Dependent Field Gradient." Journal of Chemical Physics, **42** (1), pp. 288-292.

[63] D. G. Taylor and Bushell, M. C. (1985), "The spatial mapping of translational diffusion coefficients by the NMR imaging technique," Physics in Medicine and Biology, **30** (4), pp. 345-349.

[64] Myron Tribus (1969), "Rational Descriptions, Decisions and Designs," Pergamon Press, Oxford.

[65] P. M. Woodward (1953), "Probability and Information Theory, with Applications to Radar," McGraw-Hill, N. Y. Second edition (1987); R. E. Krieger Pub. Co., Malabar, Florida.

[66] Arnold Zellner (1971), "An Introduction to Bayesian Inference in Econometrics," John Wiley and Sons, New York.

Index