

Bayesian Data-Analysis Toolbox
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Chapter 26

Phasing An Image

MRI Images present special problems for most data processing algorithms because of the use of the absolute value after the k-space data are Fourier transformed. When the absolute value is taken, the noise and the signal get multiplied. Unless the signal-to-noise in the data is very high, this cross-term can cause big problems in processing the data. However, this problem is eliminated if an absorption mode image is used because then the Fourier transform is a linear operator and if the noise was Gaussian in k-space, it remains Gaussian in the image domain. An example of an absorption mode image is shown in Fig. 26.1 as the left panel. The right panel is the same image in absolute value mode. Note that in the absorption mode image, outside the brain the noise oscillates around zero and close inspection of the images will reveal that the absorption mode image is sharper than the absolute value image. The effect is not as pronounced in images as it is in spectroscopic applications because the echos do not decay appreciably in the time needed to acquire them. Nonetheless sharper images and eliminating the noise offsets are two very strong reasons to use absorption mode images. In this Chapter we describe the Bayesian calculations needed to create an absorption mode images.

The image phasing package, Bayes Phase, estimates three phase parameters. These phase parameters may be estimated from one image and then applied to all images in an array, they may be determined for each image separately, or they may be determined for one image. In the all cases the output from the package is a series of FDF and Ascii files that may then be displayed in Vnmr, VnmrJ or they may be viewed using image browser. Additionally, these output phased images may be used to generate input data for other packages, and they may be analyzed in total to generate images of various parameter maps that are output from these other packages. For example, after a set of images have been phased individual voxel intensities may be imported into the diffusion tensor analysis and then analyzed. Or the images could be input to the Image Pixel package and then an image of the diffusion constants could be generated.

The calculations presented in this Chapter describe the imaging model and then present three separate Bayesian calculations: one for the constant phase, and then two identical calculations for the positionally dependent phase shift in each of the two spatial domains. The program that implements this calculation can process spin echo, gradient echo and EPI images. In the case of EPI images four phase parameters are needed to phase an image, in the directly detected domain an even and odd time delay are needed, additionally, one time delay is needed in the indirectly detected domain and finally one constant phase is needed. The calculations for these four phase parameters are exactly identical to the calculations for the spin echo and gradient echo phase parameters and

Figure 26.1: Absorption Model Images

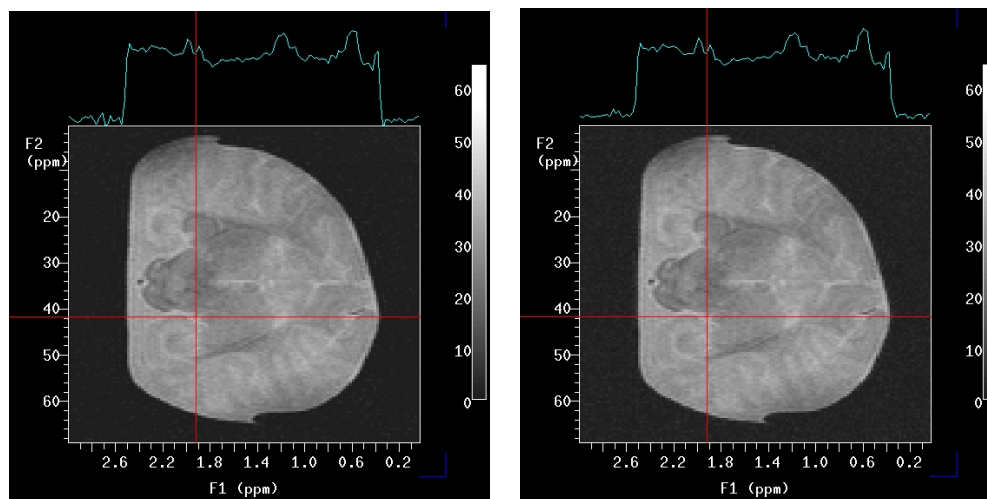


Figure 26.1: The left panel is an example of an absorption mode image while the right panel is the same image in absolute value. A single trace has been displayed on both images. Note that in the absorption image outside the brain the noise oscillates around zero and the image comes down faster on the brain boundary.

we will not have much more to say about EPI images except to note how to analyze them.

The Bayes Phase package is accessed by selecting the “Phase An Image” button on the dispatching menu. When this button is activated the interface window shown in Fig. 26.2 is displayed. The upper panel in this figure is the heart of the VnmrJ interface while the lower panel is the Vnmr interface. Both interfaces set a number of control parameters and then allow one to run the phasing algorithm.

26.1 The Bayesian Calculation

There are three phase parameters that must be determined to produce an absorption mode image: a constant phase θ , and two time delays which we will designate as τ_x and τ_y . These time delays may also be thought of as the center of the echo in the k-space, and they are analogous to the frequency dependent phase in spectroscopic measurements. In spectroscopic application, frequency dependent phase shifts are typically small. Indeed it is rare to find spectroscopic data that have frequency dependent shifts that cause more than one or two phase wraps. However, in imaging τ_x and τ_y are huge and typically cause 180° phase wraps every few points in the Fourier transform. Indeed these phase wraps are so big, that in the image domain the data look as if it has a periodic signal in it, as indeed it does.

To estimate these three phase parameters, one must relate these parameters to the data through a model. If we expand the spin density in sinc functions in the spatial domain, then in the k-space

Figure 26.2: The Interface To The Image Phasing Package

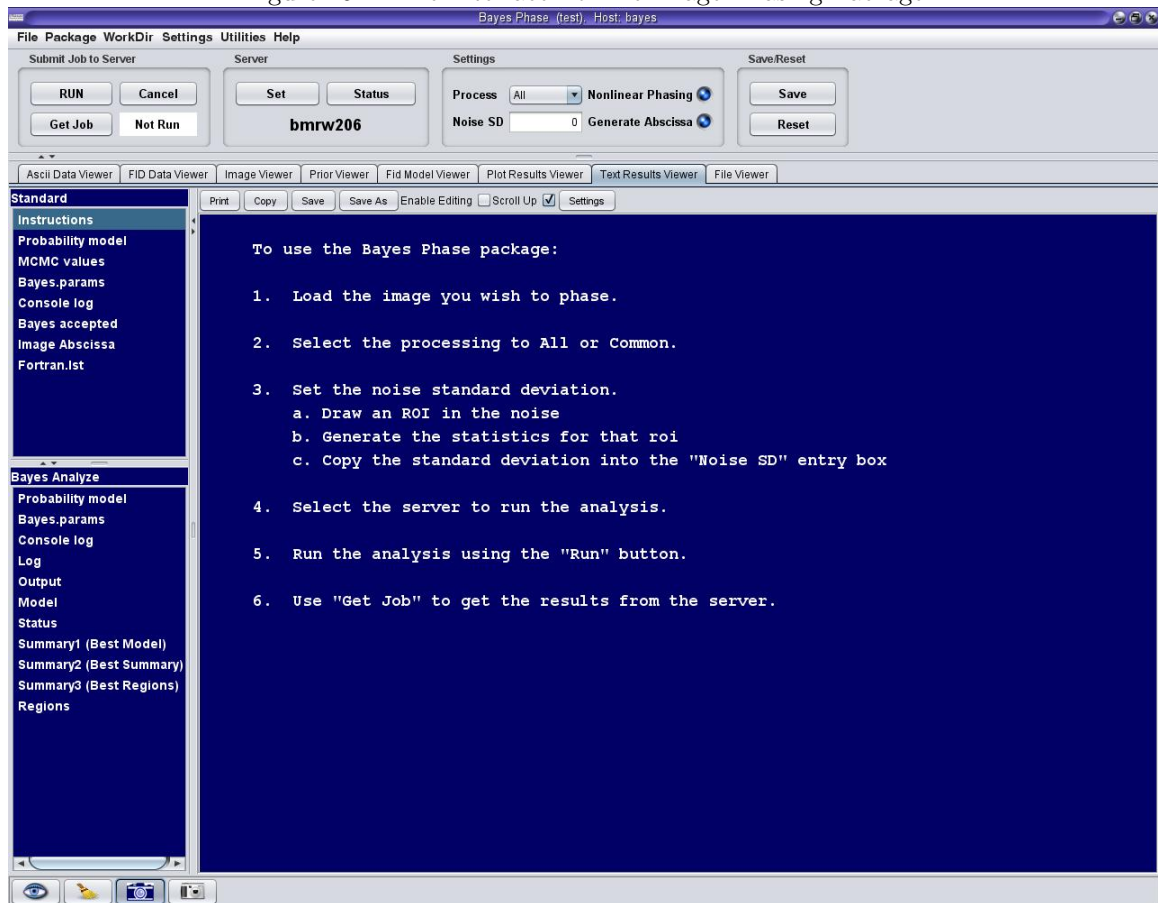


Figure 26.2: The interface to the Linear Phasing package is shown here. The Linear Phasing package outputs a series of FDF files that contain the real and imaginary parts of the phased images. These images may then be used as input to other packages. For example the are often used by the Analyze Image Pixel package.

domain the expansion is a Fourier series:

$$d_{ij} = \exp\{-i\theta\} \sum_{k=1}^{N_x} \sum_{l=1}^{N_y} A_{kl} \exp\{-2\pi i(x_k(t_{xi} + \tau_x) - 2\pi i(y_l(t_{yj} + \tau_y)))\} + \text{noise} \quad (26.1)$$

where we have designated the complex data as d_{ij} , N_x and N_y are the number of complex data values in the x and y domains, and the intensity of the spin density function at position x_k and y_l has been designated as A_{kl} . We have intentionally written this model in a way that explicitly shows that the two sums over the k -space data are time shifted inverse Fourier transforms. Note that as written the phase parameters τ_x and τ_y do participate in the sums. However the Bayesian calculations are time domain calculations, and in these calculations the sums will be over i and j and we will find that τ_x and τ_y do not participate in the sums. As a result, the Bayesian calculations may be done using fast discrete Fourier transform when N_x and N_y are powers of 2.

We will start this process by estimating τ_x . If we are only interested in τ_x , the value of both τ_y and θ are irrelevant to us. For the purposes of estimating τ_x we note that the imaging experiment just increments the value of y by a constant for each k -space acquisition. Effectively this just changes the constant phase of each new k -space acquisition. Consequently, for the purposes of estimating τ_x we will rewrite Eq. (26.1) as

$$d_{ij} = \exp\{-i\theta_j\} \sum_{k=1}^{N_x} B_{kj} \exp\{-2\pi i(x_k(t_{xi} + \tau_x))\} + \text{noise} \quad (26.2)$$

where B_{kj} are the amplitudes of the image in the j th k -space acquisition. Similarly, the phase θ_j is the constant phase in the j th k -space acquisition. Both of these quantities are related to the A_{kl} and θ through a complicated sum. Fortunately, we don't care about these expressions for estimating τ_x . Separating this model into its real and imaginary parts one has

$$d_{Rij} = \sum_{k=1}^{N_x} B_{kj} M_{Rki} + \text{noise} \quad (26.3)$$

for the real data, and

$$d_{Iij} = \sum_{k=1}^{N_x} -B_{kj} M_{Iki} + \text{noise} \quad (26.4)$$

for the quadrature data where

$$M_{Rki} \equiv \cos(\theta) \cos(2\pi x_k[t_{xi} + \tau_x]) + \sin(\theta) \sin(2\pi x_k[t_{xi} + \tau_x]) \quad (26.5)$$

and

$$M_{Iki} \equiv \cos(\theta) \sin(2\pi x_k[t_{xi} + \tau_x]) - \sin(\theta) \cos(2\pi x_k[t_{xi} + \tau_x]). \quad (26.6)$$

In this model the data may be thought of as N_y different data sets each of them bearing on the value of τ_x . If each data set contributes independent information about τ_x , then the posterior probability will just be the product of the probabilities for τ_x in each data set separately. Consequently, the marginal posterior probability for τ_x can be factored to obtain

$$P(\tau_x|DI) = \int d\sigma \prod_{j=1}^{N_y} \int dB_{1j} \dots dB_{N_x j} d\theta_j P(B_{1j} \dots B_{N_x j} \theta_j \sigma | D_j I) \quad (26.7)$$

where D_j is just the data for the j th k-space acquisition.

The right-hand side of this equation is factored using Bayes' theorem to obtain:

$$P(\tau_x|DI) \propto \int d\sigma \prod_{j=1}^{N_y} \int dB_{1j} \dots dB_{N_xj} d\theta_j P(B_{1j} \dots B_{N_xj} \theta_j \sigma | I) P(D_j | B_{1j} \dots B_{N_xj} \theta_j \sigma I). \quad (26.8)$$

Finally, the joint prior probability for the parameters is factored using the product rule to obtain

$$P(\tau_x|DI) \propto \int d\sigma P(\sigma|I) \prod_{j=1}^{N_y} \int dB_{1j} \dots dB_{N_xj} d\theta_j \times P(\theta_j|I) P(B_{1j} \dots B_{N_xj}|I) P(D_j|B_{1j} \dots B_{N_xj} \theta_j \sigma I) \quad (26.9)$$

where we have not factored the prior probability for the amplitudes, $P(B_{1j} \dots B_{N_xj}|I)$, into independent prior probabilities because we are going to assign a correlated prior to the amplitudes. That is to say we are going to take into account the fact that images tend to be smoothly varying and that adjacent voxels tend to be very nearly equal.

We have now reached the point in the Bayesian calculation where one has no choice but to assign a numerical value to represent each of these probabilities. The prior probability for the noise standard deviation, $P(\sigma|I)$, will be assigned a Jeffreys' prior

$$P(\sigma|I) \propto \frac{1}{\sigma}. \quad (26.10)$$

The prior probability for the phase, $P(\theta_j|I)$, will be assigned a uniform prior probability and this prior will restrict the integration over the phase to zero to 2π .

In assigning the prior probability for the amplitudes we wish to take into account the fact that adjacent amplitudes tend to be nearly equal. Of course, there are always exceptions to this, but nonetheless, in this analysis we are going to put in a prior that will try and make adjacent voxels equal. Here is how this is done. If $B_{kj} \approx B_{k+1j}$ then

$$B_{kj} \approx B_{k+1j} \Rightarrow B_{kj} - B_{k+1j} \approx 0 \Rightarrow \sum_{k=1}^{N_x-1} (B_{kj} - B_{k+1j})^2 \text{ is small.} \quad (26.11)$$

If the principle of Maximum Entropy is used to assign a prior probability that imposes this condition, Maximum Entropy will lead to a Gaussian assignment for the prior. This Gaussian will be written as

$$P(B_{1j} \dots B_{N_xj}|I) \propto \left(\frac{\sigma}{\beta}\right)^{-N_x} |U_{kl}|^{-\frac{1}{2}} \exp \left\{ - \sum_{k=1}^{N_x} \sum_{l=1}^{N_x} \frac{B_{lj} \beta^2 U_{kl} B_{kj}}{2\sigma^2} \right\} \quad (26.12)$$

where the matrix U_{kl} is a tri-diagonal matrix having [-1, 2,-1] as its three non-zero diagonals and β expresses how strongly we believe adjacent voxels should be equal. In the program that implements this calculation $\beta = 0.1$, so the prior says that we think small oscillations, on the order of 0.01 of the maximum signal value are probably noise. Note we are using this condition only in the calculation of τ_x , we do not use this condition in generating the final images. This condition is equivalent to imposing a smoothness constraint on the first derivative of the image and because the Fourier transform is symmetric this prior imposes what is often referred to as a circular boundary condition.

If we assign the likelihood using a Gaussian, the joint posterior probability for τ_x , Eq. (26.9), is given by:

$$P(\tau_x|DI) \propto \int \frac{d\sigma}{\sigma} \prod_{j=1}^{N_y} \int d\theta_j dB_{1j} \dots dB_{N_x j} \sigma^{-3N_x} \exp \left\{ -\frac{Q_j}{2\sigma^2} \right\} \quad (26.13)$$

where we have dropped some constants that cancel when this distribution is normalized. The quantity Q_j is given by

$$Q_j \equiv \sum_{k=1}^{N_x} \sum_{l=1}^{N_x} B_{lj} \beta^2 U_{kl} B_{kj} + \sum_{i=1}^{N_x} \left(d_{Rij} - \sum_{k=1}^{N_x} B_{kj} M_{Rki} \right)^2 + \left(d_{Iij} + \sum_{k=1}^{N_x} B_{kj} M_{Iki} \right)^2 \quad (26.14)$$

and, up to the term from the prior probability for the amplitudes, is Chi-squared evaluated for each of the k-space data sets. If we substitute the definitions of M_{Rki} and M_{Iki} , Eqs. (26.5 and 26.6) respectively then we obtain:

$$Q_j \equiv N_x \overline{d_{xj}^2} - 2 \sum_{i=1}^{N_x} B_{ij} [\cos \theta F_{Rij} + \sin \theta F_{Iij}] + \sum_{k=1}^{N_x} \sum_{l=1}^{N_x} B_{kj} B_{lj} V_{klj} \quad (26.15)$$

with

$$V_{klj} \equiv N_x \delta_{kl} + \beta^2 U_{kl}, \quad (26.16)$$

where δ_{kl} is a delta function,

$$\overline{d_{xj}^2} \equiv \frac{1}{N_x} \sum_{i=1}^{N_x} d_{ij}^2 \quad (26.17)$$

is the mean-square data value in the j th k-space acquisition. The projections of the data onto the model,

$$F_{Rij} \equiv \sum_{i=1}^{N_x} d_{Rij} \cos(2\pi x_k [t_{xi} + \tau_x]) - d_{Iij} \sin(2\pi x_k [t_{xi} + \tau_x]) \quad (26.18)$$

and

$$F_{Iij} \equiv \sum_{i=1}^{N_x} d_{Rij} \sin(2\pi x_k [t_{xi} + \tau_x]) + d_{Iij} \cos(2\pi x_k [t_{xi} + \tau_x]), \quad (26.19)$$

are essentially the real and imaginary parts of a time shifted discrete Fourier transform. While we have not separated the time delays from the other parts of the Fourier transform, a simple trigonometric identity will reduce these quantities to linear combinations of the real and imaginary parts of the discrete Fourier transform.

The functional form of Q_j is a quadratic in the B_{kj} , so the integrals over the B_{kj} are Gaussian quadrature integrals. Such integrals are easily evaluated and we only give the results here, one obtains

$$P(\tau_x|DI) \propto \int \frac{d\sigma}{\sigma} \prod_{j=1}^{N_y} |V_{klj}|^{-\frac{1}{2}} \int d\theta_j \sigma^{-2N_x} \exp \left\{ -\frac{N_x \overline{d_{xj}^2} - \sum_{i=1}^{N_x} \hat{B}_{ij} T_{ij}}{2\sigma^2} \right\} \quad (26.20)$$

where

$$T_{ij} \equiv \cos \theta F_{Rij} + \sin \theta F_{Iij} \quad (26.21)$$

and

$$\hat{B}_{ij} = \cos \theta \hat{a}_{ij} + \sin \theta \hat{b}_{ij} \quad (26.22)$$

with

$$\hat{a}_{ij} = V_{ikj}^{-1} F_{Rkj} \quad \text{and} \quad \hat{b}_{ij} = V_{ikj}^{-1} F_{Ikj}. \quad (26.23)$$

The quantities \hat{a}_{ij} and \hat{b}_{ij} are essentially the real and imaginary parts of the discrete Fourier transform, while \hat{B}_{ij} is the expected amplitude of the signal in the phased image.

The integral over the phase is tedious and not very illuminating, and we only sketch how this integral is evaluated. One begins by taking the sufficient statistic, the sum in Eq. (26.20), and substitutes the definitions of T_{ij} and \hat{B}_{ij} . This results in a quadratic expression in $\cos \theta$ and $\sin \theta$. These quadratics are then reduced to $\sin(2\theta)$ and $\cos(2\theta)$ using trigonometric identities. The resulting expression may then be rewritten in terms of $\cos(2\theta + \psi)$, where ψ is a phase. In this form the integral is of the form $\exp\{\cos(\phi)\}$ which is the integral representation of the I_0 Bessel function, one obtains

$$P(\tau_x|DI) \propto \int \frac{d\sigma}{\sigma} \prod_{j=1}^{N_y} |V_{klj}|^{-\frac{1}{2}} \sigma^{-2N_x} \exp \left\{ -\frac{N_x \overline{d_{xj}^2} - \frac{1}{2} \sum_{i=1}^{N_x} (\hat{a}_{ij} F_{Rij} + \hat{b}_{ij} F_{Iij})}{2\sigma^2} \right\} I_0 \left(\frac{\sqrt{W_j^2 + X_j^2}}{2\sigma^2} \right) \quad (26.24)$$

with

$$W_j = \sum_{i=1}^{N_x} \frac{\hat{a}_{ij} F_{Rij} - \hat{b}_{ij} F_{Iij}}{2} \quad (26.25)$$

and

$$X_j = \sum_{i=1}^{N_x} \frac{\hat{a}_{ij} F_{Iij} + \hat{b}_{ij} F_{Rij}}{2}. \quad (26.26)$$

We note in passing that the quantity

$$\psi_j = -\frac{1}{2} \tan^{-1} \left(\frac{X_j}{W_j} \right) \quad (26.27)$$

is the estimated constant part of the phase for each of the k-space acquisitions. We mention this because in the full calculation, a quantity almost identical to this will appear as the estimated constant phase for the entire data set.

In this form the integral over the standard deviation of the noise prior probability, σ , is not easily represented in closed form. Fortunately, there is a simple easy approximation that is good to many decimal places around the maximum in Eq.(26.24). For large argument the I_0 Bessel function is nearly exponential, then Eq.(26.24) is very nearly equal to

$$P(\tau_x|DI) \approx \int \frac{d\sigma}{\sigma} \prod_{j=1}^{N_y} |V_{klj}|^{-\frac{1}{2}} \sigma^{-2N_x} \exp \left\{ -\frac{N_x \overline{d_{xj}^2} - \frac{1}{2} \sum_{i=1}^{N_x} (\hat{a}_{ij} F_{Rij} + \hat{b}_{ij} F_{Iij}) - \sqrt{W_j^2 + X_j^2}}{2\sigma^2} \right\} \quad (26.28)$$

and the integral over the standard deviation may be transformed into a gamma function and we omit the details of evaluating this integral, one obtains

$$P(\tau_x|DI) \propto \prod_{j=1}^{N_y} |V_{klj}|^{-\frac{1}{2}} \left[N_x \overline{d_{xj}^2} - \frac{1}{2} \sum_{i=1}^{N_x} (\hat{a}_{ij} F_{Rij} + \hat{b}_{ij} F_{Iij}) - \sqrt{W_j^2 + X_j^2} \right]^{-N_x}. \quad (26.29)$$

This probability density function is of the form of Student's t -distribution, and it is this t -distribution that is computed in the phasing algorithm.

In addition to estimating τ_x one also needs to compute the posterior probability for τ_y . However, all one needs to do is to exchange the role of x and y and in the above equations to obtain $P(\tau_y|DI)$. Consequently, we do not give this calculation. Finally, one needs to compute the posterior probability for $P(\theta|DI)$, but we already noted that the calculation is essentially identical to Eq. (26.27). Indeed all that needs to be done is to replace the sums over x by a sum over x and y and then Eq. (26.27) will give the expected value of the phase.

So here is how the calculation is actually implemented. One first computes the fast discrete Fourier transform and uses these projections to compute posterior probability for τ_x on a coarse grid. In dimensionless units τ_x varies from $N_x/4 \leq \tau_x \leq 3N_x/4$. Outside this range the posterior probability is aliased and no additional information is available. After finding the location of the peak on this coarse grid, the algorithm does a binary search for the maximum posterior probability estimate of τ_x . Then using the estimated value of τ_x the positionally dependent phase is unwrapped in the x domain. This calculation is then repeated in the y domain and the phase is again unwrapped. The constant phase is then computed. However, there is an ambiguity in the constant phase. If the calculated value of the constant phase is Θ , then the phase that gives positive amplitudes could be Θ or $\Theta + 180^\circ$. Before setting the constant phase the program does a quick calculation to determine which phase is appropriate and finally the constant part of the phase is unwrapped. After all of the phases have been set, the program outputs the phased images as PDF files. These PDF files are what are displayed in VNMR.

26.2 Using The Package

To use the phasing package begin by loading an image. This may be done using the Vnmr files menu or you may use the **Load An Image** on the window, see Fig. 26.2. In VnmrJ the corresponding function is done on the housekeeping folder using the CWD file menu. When an image is loaded under Vnmr, the macros test to see if the image has been previously analyzed. If it has and the current setting of the parameters are the same as when the images were phase the run indicator is turned on and the package is set run. You may rerun the images at any time but assuming the previous settings of the variables are OK, there is no need to do this.

After loading an image, specify whether the image is a spin echo or EPI image. This is done using the **Image Type** menu. Here the term spin echo means only that the image may be phased using three phase parameters, so gradient echo images should be selected as spin echo. While EPI means that 4 phase parameters are needed to phase an image: the constant phase, τ_y and an even and odd delay, τ_{ex} and τ_{ox} , in x .

Next indicate how the images are to be processed using the **process** menu. The choices are All, Common or One, where "All" means that each image is to be phased using parameters specific to that image. "Common" means that phase parameters are to be computed from the currently

Figure 26.3: Linear Phasing Package The Console Log

Array	Slice	Delay X	Delay Y	Phase
33	1	66.37122551	47.85130018	285.95947785
1	1	66.18384758	47.96787733	308.70159650
34	1	66.20887199	47.97886366	304.08678779
2	1	66.20948234	47.96055311	306.64428485
35	1	66.35840813	47.91508192	292.95579385
3	1	66.21192375	47.97764295	306.10371565
36	1	66.26502434	47.90165418	294.32695098
4	1	66.23938957	47.95567030	305.71194166
37	1	66.24671379	48.01442248	302.01416187
5	1	66.29920402	47.96909803	302.93402804
38	1	66.24671379	47.94590467	300.11338126
6	1	66.26075188	47.96177381	303.08474711
39	1	66.34314934	48.01747424	299.16341694
7	1	66.20398918	47.96299451	303.84929962
40	1	66.30774895	47.87754530	292.07343083
8	1	66.20765129	47.97398084	304.35076867
41	1	66.43714348	47.64805311	266.41805910
9	1	66.20368400	47.96421522	305.24927395
42	1	66.44019523	47.96787733	292.28161251

Figure 26.3: The Phasing routine does write the value of the phase parameter to the mcmc.values file. The exact format of this file varies somewhat between spin echo images and EPI, EPI images have a fourth column: the even and odd τ_x value.

displayed image and then those phase parameters are to be applied to every image. Finally, “One” means to compute the phase parameters for the currently displayed image.

There are a number of widgets on the interface that are used to control the display and used to set the image sizes. The entry boxes labeled “fn” and “fn1” are used to enter the sizes of the Fourier transforms. If these sizes differ from the “np” and 2 times “nv” the program does the calculations using “np” and “nv” sizes and then computes and phases the final images at the “fn” and “fn1” values.

Finally, the entry boxes **cf**, **Display Array Element** and **Display** many be used to control which image is being displayed. In all cases if the phasing algorithm has been run, then the phased image is displayed, otherwise the image is displayed in absolute value mode. Changing “cf” will cause different slices to be displayed. Similarly, changing “Display Array Element” will display an image from the new array element. Finally, changing “Display” from Real to Imaginary will cause the imaginary part of the image to be displayed. Note this last widget does nothing if the phase algorithm has not be run.

The phasing routine does write the phases to the “mcmc.values” file located in the BayesOther-Analysis directory in the current experiment. An example of this file is shown in Fig. 26.3 The phasing algorithm does use multiple threads, but not to the extent that most other algorithms do. In the case of the phasing algorithm if multiple images are to be phased each image is dispatched

to a separate thread to run. This is indicated in the output list because the order of the “array” index is mixed up. This output is simply written as each thread completes phasing an image, so the order can get mixed up. Note that in the case of the image processed to produce this figure the delay in both x and y was very stable, while the constant phase did vary a little. However, even with this variation it would have been possible to phase this image using a single common set of phase parameters.

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Index

- A_k definition, 349
- $H_{j\ell}(t_i)$ definition, 349
- λ_ℓ definition, 349
- g_{jk} eigenvalue, 349
- Abscissa, **437**
 - Computational, 436
 - Generating, 427
 - Loading, 39
 - Multicolumn, 437
 - Number Of Columns, 458
 - Total Data Values, 456
- Aliases, 113, **126**
- Amplitudes orthonormal definition, 349
- Analyze Image Pixel Package, **411**
 - Modification History, 413
 - Phased Images, 397
 - Reports
 - Bayes Accepted, 413
 - Using, 413
 - Viewers
 - Fortran/C Models, 411
 - Image, 411
 - Prior Probabilities, 413
 - Widgets
 - Abscissa File, 411
 - Build, 411
 - Find Outliers, 411
 - Get Statistics, 413
 - System, 411
 - User, 411
- Analyze Image Pixel Unique Package, **423**
 - Highlight
 - Abscissa, 425
 - Data, 425
 - Input Image
 - Abscissa, 423
 - Data, 423
 - Reports
 - Bayes Accepted, 425
 - Console Log, 425
 - McMC Values, 425
 - Using, 425
 - Viewers
 - Fortran/C Models, 423
 - Image, 423
 - Prior Probabilities, 425
 - Widgets
 - Build, 423
 - Find Outliers, 423
 - Get Statistics, 425
 - System, 423
 - User, 423
- Ascii Data Viewer, **53**
- Assigning Probabilities, **118**
- Bandwidth, **111, 127**
- Bayes Analyze Package, **155**
 - Levenberg-Marquardt , 171
 - Step, 194
 - Algorithm, 175
 - Amplitudes, 197, 198
 - Bayes Model, 159, 161
 - Bayesian Calculations, 167
 - Bruker, 162
 - Build BA Model, 159
 - Covariance, 174
 - Default Parameters Settings, 155
 - Error Messages, 200
 - Fid Model Viewer, 160
 - Interface, 156
 - Likelihood
 - Gaussian, 158
 - Student's t -distribution, 158

- Log File, 193, 195
- Lorentzian lineshape, 161
- Marking Resonances, 157
- Model
 - J_o , 165
 - J_p , 165
 - J_s , 165
 - Amplitude, 163, 164
 - Bessel Function, 163
 - Constants Models, 157
 - Correlated, 157, 162, 164
 - Equation, 161, 164, 164
 - First Order Phase, 157, 162, 164
 - First Point, 162, 164
 - Gaussian, 163
 - Imaginary Constant, 164
 - Multi-Exponential, 163
 - Multiple Data Sets, 165
 - Multiplet Order, 164
 - Multiplet Orders, 164
 - Multiplets, 162
 - Multiplets of Multiplets, 164
 - Non-Lorentzian, 163
 - Offsets, 162
 - Real Constant, 164
 - Relative Amplitude, 164–166
 - Resonance Frequency, 165
 - Shim Order, 163
 - Shimming, 166
 - Shimming Order, 164
 - Uncorrelated, 157, 162, 164
 - Zero Order Phase, 157, 162, 164
- Model Interface, 160
- Multiplets, 158
- Newton-Raphson, 171
- Noise File, 158
- Noise Standard Deviation, 158
- Outputs
 - Bayes.accepted File, 177
 - bayes.log.nnnn File, 177, 193, 193
 - bayes.model.nnnn File, 177, 185, 197, 197
 - bayes.noise File, 180
 - bayes.noise.nnnn File, 158, 180
 - bayes.output.nnnn File, 176, 186, 186
 - bayes.params File, 176, 177
 - bayes.params.nnnn File, 176, 177, 177
 - bayes.probabilities.nnnn File, 177, 190, 190
 - bayes.status.nnnn File, 177, 196, 200
 - bayes.summary1.nnnn File, 177, 198, 198
 - bayes.summary2.nnnn File, 177, 199, 199
 - bayes.summary3.nnnn File, 177, 200, 200
 - Global Parameters, 182, 183
 - Model File, 184
 - Probabilities file, 191
 - Zero Order Phase, 182
- Parameter File
 - Activate Shims, 180
 - Analysis Directory, 178
 - By Fid, 181
 - Data Type, 180
 - Default Model, 181
 - Directory Organization, 180
 - Fid Model Name, 178
 - File Version, 178
 - First Fid, 181
 - First Order Phase, 180, 183
 - Imaginary Constant, 184
 - Last Fid, 181
 - lb, 182
 - Maximum Candidates, 182
 - Maximum New Resonances, 182
 - Model Fid Number, 181
 - Model Name, 184
 - Model Names, 181
 - Model Number, 184
 - Model Points, 181
 - Multiplets of Multiplets, 185
 - Noise Start, 181
 - Numerical Parameters, 178
 - Output Format, 180
 - Prior Odds, 182
 - Procparr, 178
 - Real Constant, 184
 - Relative Amplitude, 183
 - Resonance Model, 185
 - Shim Order, 182
 - Spectrometer Frequency, 182
 - Text Parameters, 178
 - Total Complex Data Values, 181
 - Total Data Values, 181
 - Total Sampling Time, 182
 - True Reference, 182

- Units, 180
- Use Noise StdDev, 180
- User Reference, 182
- Prior Probabilities, 167
- Probabilities File, 191
- Product Rule, 168
- Relative Amplitude, 167
- Remove Resonances, 159
- Reports
 - Bayes Status, 155
- Save/Reset, 159
- Search, 166
 - Levenberg-Marquardt , 166
- Short Parameter Description, 195
- Siemens, 162
- Status File, 196
- Steepest Descents, 173
- Sum Rule, 168
- Summary File, 198
- Summary Reports, 176
- Summary2, 199
- Summary3, 201
- Units, 161
- Using, 157
- Varian/Agilent, 162
- Widgets, 155
 - By, 158, 176
 - First Point, 157, 163
 - From, 158, 176
 - Imag Offset, 163
 - Imaginary Offset, 157
 - Mark, 159
 - Max New Res, 157
 - New, 159
 - Noise, 158
 - Phase, 157
 - Primary, 158
 - Real Offset, 157, 163
 - Remove, 159
 - Remove All, 159
 - Reset, 159, 193
 - Restore, 159
 - Save, 159
 - Secondary, 159
 - Shim Order, 157, 163
 - Signal, 158
 - To, 158, 176
- Bayes Find Resonances Package, **239**
 - Bayesian Calculations, 241
 - Current Fid, 239
 - Model Equation, 241
 - Number of data sets, 239
 - Phase Model
 - Automatic, 239, 242
 - Common, 239, 242
 - Independent, 239, 242
 - Prior Probabilities, 243–245
 - Reports
 - Bayes Accepted, 241, 246
 - Condensed, 246
 - Console log, 246
 - MCMC Values, 246
 - Prob Model, 246
 - Using, 239, 241
 - Viewers
 - Fid Data, 240
 - Fid Model, 240, 246
 - File, 246
 - Plot Results, 246
 - Text, 246
 - Widgets
 - Build FID Model, **240, 241, 246**
 - Constant, 239, 242
 - First Trace, 239
 - Last Trace, 239
 - Model Fid Number, 241
 - Phase Model, 239, 242
- Bayes Home Directory, 45, **49**
- Bayes Manual pdf, 469
- Bayes Metabolite Package
 - Widgets
 - Shift Left, 222
 - Shift Right, 222
- Bayes Metabolite Package, **219**
 - Aligning Resonances, 221
 - Bayesian Calculation, 225
 - Metabolite Locations, 221
 - Model Equation, 223
 - Reports
 - Bayes Accepted, 221, 238
 - Condensed, 238
 - Console log, 238

- McMC Values, [238](#)
- Prob Model, [238](#)
- Viewers
 - Fid Data, [219](#)
 - Fid Model, [221](#), [236](#)
 - File, [222](#), [238](#)
 - Metabolite, [221](#)
 - Plot Results, [238](#)
 - Text, [238](#)
- Widgets
 - Fid Model, [221](#)
 - Fid Model Viewer, [221](#)
 - Load System Metabolite File, [219](#)
 - Load System Resonance File, [221](#)
 - Load User Metabolite File, [219](#)
 - Load User Resonance File, [221](#)
 - Shift Left, [221](#)
 - Shift Right, [221](#)
- Bayes Model, [159](#), [159](#)
- Bayes Test Data Package, [427](#)
 - Parameters, [431](#)
 - Reports
 - Bayes Accepted, [428](#)
 - Condensed, [429](#)
 - McMC Values, [429](#), [431–433](#)
 - Viewers
 - Fortran/C Models, [427](#)
 - Image, [428](#)
 - Prior Probabilities, [427](#)
 - Text Data, [430](#)
 - Text Results, [429](#)
 - Widgets
 - # Images, [427](#)
 - # Slices, [427](#)
 - Abscissa, [427](#)
 - ArrayDim, [427](#)
 - Build, [427](#)
 - Get Job, [428](#)
 - Max Value, [427](#)
 - Noise SD, [427](#)
 - Parameter Ranges, [428](#)
 - Pe, [427](#)
 - Ro, [427](#)
 - Run, [428](#)
 - Set (server), [428](#)
 - Status, [428](#)
- Bayes' Theorem, [100](#), [139](#), [145](#), [153](#), [167](#), [211](#), [226](#), [243](#), [252](#), [261](#), [269](#), [278](#), [288](#), [295](#), [306](#), [314](#), [315](#), [317](#), [318](#), [331](#), [333](#), [343](#), [370](#), [399](#), [407](#), [439](#)
- Bayes.accepted
 - Body, [77](#)
 - Header, [76](#)
- Behrens-Fisher Package, [311](#)
 - Bayesian Calculations
 - Derived Probabilities, [320](#)
 - Different Mean And Same Variance, [318](#)
 - Different Mean And Variance, [319](#)
 - Parameter Estimation, [321](#)
 - Same Mean And Different Variance, [317](#)
 - Same Mean And Variance, [315](#)
 - Model Equation
 - Different Mean And Same Variance, [318](#)
 - Different Mean And Variance, [319](#)
 - Same Mean And Different Variance, [317](#)
 - Same Mean And Variance, [315](#)
 - Number of data sets, [311](#)
 - Parameter Listing, [323](#)
 - Prior Probabilities
 - Different Mean And Same Variance, [318](#)
 - Different Mean And Variance, [319](#)
 - Same Mean And Different Variance, [317](#)
 - Same Means And Same Variance, [315](#)
 - Reports
 - Bayes Accepted, [311](#), [322](#)
 - Condensed, [322](#)
 - Console Log, [322](#), [323](#)
 - McMC Values, [322](#), [323](#)
 - Prob Model, [322](#)
 - Using, [311](#)
- Viewers
 - File, [322](#)
 - Plot Results, [322](#), [324](#)
 - Prior Probabilities, [311](#)
 - Text, [322](#)
- Widgets
 - None, [311](#)
- Big Endian, [471](#), [473](#)
- Big Magnetization Transfer Package, [259](#)
 - Bayesian Calculations, [259](#)
 - Files
 - Bayes Analyze, [264](#)

- Fid, [263](#)
- Peak Pick, [262](#)
- Model Equation, [261](#)
- Number of data sets, [259](#)
- Prior Probabilities, [261](#)
- Reports
 - Bayes Accepted, [259](#), [262](#)
 - Condensed, [262](#)
 - Console log, [262](#)
 - McMC Values, [262](#)
 - Prob Model, [262](#)
- Using, [259](#)
- Viewers
 - Ascii Data, [259](#)
 - File, [262](#)
 - Prior Probabilities, [259](#)
 - Text, [262](#)
- Widgets
 - Find Outliers, [259](#)
- Big Peak/Little Peak Package, [207](#)
- Bayesian Calculations, [209](#)
- Fid Analyzed, [207](#)
- Model Equation, [210](#)
 - Metabolites, [209](#)
 - Solvent, [210](#)
- Number of data sets, [207](#)
- Prior Probabilities
 - Metabolite, [207](#)
 - Solvent, [207](#)
- Removing Resonances, [207](#)
- Reports
 - Bayes Accepted, [209](#), [216](#)
 - Condensed, [216](#)
 - Console log, [216](#)
 - McMC Values, [216](#)
 - Prob Model, [216](#)
- Using, [207](#)
- Viewers
 - File, [216](#)
 - Model, [209](#)
 - Plot Results, [216](#)
 - Prior Probabilities, [207](#)
 - Text, [216](#)
- Widgets
 - Metabolite, [207](#)
 - Solvent, [207](#)
- Binned Density Function Estimation, [355](#)
- Binned Histogram Package
 - Reports
 - Bayes Accepted, [357](#)
 - Viewers
 - Ascii, [355](#)
- Binned Histograms Package
 - Using, [357](#)
 - Viewers
 - Prior Probabilities, [355](#)
- Bloch-McConnell Equations, [267](#), [277](#)
- Changing the Bayes Home Directory, [469](#)
- Compilers, [29](#)
 - CC, [29](#), [455](#)
 - Fortran, [29](#), [455](#)
- Correlations, [91](#)
- Diffusion Tensor Package, [247](#)
 - Ascii File Formats, [247](#), [254](#), [255](#)
 - Bayesian Calculations, [249](#)
 - Prior Probabilities
 - Δ , [254](#)
 - Γ , [254](#)
 - δ , [254](#)
 - σ , [253](#)
 - Amplitudes, [253](#)
 - Eigenvalues, [253](#)
 - Euler Angles, [253](#)
 - Likelihood, [253](#)
 - Parameter, [254](#)
- Reports
 - Bayes Accepted, [247](#), [255](#)
 - Condensed, [255](#)
 - Console log, [255](#)
 - McMC Values, [255](#)
 - Prob Model, [255](#)
- Symmetries, [253](#)
- Using, [247](#)
- Viewers
 - File, [247](#), [255](#)
 - Plot Results, [255](#)
 - Prior Probabilities, [247](#), [253](#)
 - Text, [255](#)
- Widgets
 - Abscissa Options, [248](#)

- Find Outliers, [247](#)
- Include Constant, [247](#), [248](#), [255](#)
- Tensor Number, [247](#), [248](#), [255](#)
- Use b Matrix, [255](#)
- Use b Vectors, [255](#)
- Use g Vectors, [254](#)
- Discrete Fourier Transform, [110](#), [113](#), [123](#)
- Enter Ascii Model Package, [329](#)
 - Bayesian Calculations, [332](#)
 - Marginalization, [332](#)
 - No Marginalization, [331](#)
 - Fortran/C Models, [330](#), [335](#)
 - Model Equation
 - Marginalization, [331](#)
 - No Marginalization, [331](#)
 - Output Names
 - Derived, [335](#)
 - Parameters, [335](#)
 - Reports
 - Bayes Accepted, [331](#), [335](#)
 - Bayes Params, [335](#)
 - Condensed, [335](#)
 - Console log, [335](#)
 - McMC Values, [335](#)
 - Prob Model, [335](#)
 - Using, [331](#)
 - Viewers
 - Ascii Data, [329](#)
 - File, [335](#)
 - Fortran/C Models, [329](#)
 - Plot Results, [335](#)
 - Prior Probabilities, [329](#)
 - Text, [335](#)
 - Widgets
 - Build, [329](#)
 - Find Outliers, [329](#)
 - System, [329](#)
 - User, [329](#)
- Enter Ascii Model Selection Package, [341](#)
 - Bayesian Calculations
 - Marginalization, [346](#)
 - No Marginalization, [344](#)
 - Fortran/C Models, [341](#), [343](#), [353](#)
 - Model Equation, [343](#)
 - No Marginalization, [343](#)
 - With Marginalization, [347](#)
 - Output Names
 - Derived, [354](#)
 - Parameters, [353](#)
 - Reports
 - Bayes Accepted, [343](#), [353](#)
 - Condensed, [353](#)
 - Console log, [353](#)
 - McMC Values, [353](#)
 - Params File, [353](#)
 - Prob Model, [353](#)
 - Using, [343](#)
 - Viewers
 - Ascii Data, [341](#)
 - File, [353](#)
 - Fortran/C Models, [341](#)
 - Plot Results, [353](#)
 - Prior Probabilities Not Used, [341](#)
 - Text, [353](#)
 - Widgets
 - Build Not Used, [341](#)
 - Find Outliers, [341](#)
 - System, [341](#)
 - User, [341](#)
- Errors In Variables Package, [303](#)
 - Ascii File Formats
 - Errors In X and Y Known, [303](#), [309](#)
 - Errors In X Known, [303](#), [309](#)
 - Errors In Y Known, [303](#), [309](#)
 - Errors Unknown, [303](#), [309](#)
 - Bayesian Calculations, [305](#)
 - Data Error Bars, [303](#)
 - Files
 - Ascii, [303](#)
 - Bayes Analyze, [303](#)
 - Peak Pick, [303](#)
 - Model Equation, [305](#)
 - Number of data sets, [303](#)
 - Reports
 - Bayes Accepted, [305](#), [309](#)
 - Condensed, [309](#)
 - Console log, [309](#)
 - McMC Values, [309](#)
 - Prob Model, [309](#)
 - Using, [305](#)
 - Viewers

- Ascii Data, [303](#)
 - File, [309](#)
 - Plot Results, [309](#)
 - Text, [309](#)
- Widgets
 - Given Errors In, [303](#)
 - Order, [303](#)
- Exponentials
 - Given Package, [137](#)
 - Inversion Recovery Package, [151](#)
 - Magnetization Transfer Package, [267](#)
 - Unknown Number of Package, [143](#)
- Fid Data Viewer, [53](#)
- Fid Model Viewer, [68](#)
- File Format
 - Ascii, [436](#)
- File Viewer, [80](#)
- Files
 - 4dfp, [59](#), [428](#), [430](#), [470](#), [471](#)
 - Header, [473](#)
 - Reading, [471](#)
 - Abscissa, [39](#), [77](#), [470](#)
 - afh, [53](#)
 - ASCII, [35](#), [36](#)
 - Ascii, [53](#), [54](#), [435](#)
 - k*-space, [437](#)
 - Abscissa, [435](#), [436](#), [437](#)
 - Data, [435](#)
 - Image, [436](#)
 - Bayes Analyze, [36](#)
 - Bayes.accepted, [51](#), [76](#)
 - Bayes.params, [76](#), [79](#)
 - Bayes.prob.model, [447](#)
 - BayesManual.pdf, [469](#)
 - Condensed, [77](#), [78](#)
 - Console.log, [76](#), [79](#), [465](#)
 - dir.info, [470](#)
 - fid, [470](#), [470](#)
 - ASCII, [36](#)
 - ffh, [56](#)
 - Model, [68](#), [70](#)
 - procpa, [470](#)
 - Siemens Raw, [36](#)
 - Siemens Rda, [36](#)
 - Spectroscopic, [53](#)
 - Varian fid, [36](#)
 - Fortran/C Models, [42](#), [455](#), [457](#), [458](#), [465](#)–[467](#)
 - Images
 - 4dfp, [38](#)
 - Binary, [38](#)
 - Bruker 2dseq, [38](#)
 - Bruker stack, [38](#)
 - DICOM, [38](#)
 - FDF, [38](#)
 - Multi-Column Text, [38](#)
 - Siemens IMA, [38](#)
 - k*-space
 - Text, [36](#)
 - Varian fid, [36](#)
 - mcmc.values, [76](#), [449](#)
 - Model Listing, [77](#)
 - prob.model, [76](#)
 - procpa, [470](#)
 - Raw, [36](#)
 - RDA, [36](#)
 - Statistics, [65](#)
 - System.err.txt, [469](#)
 - System.out.txt, [469](#)
 - Varian fid, [36](#)
 - WaterViscosityTable, [469](#)
- Fortran/C Model Viewer, [93](#)
 - Popup Editor, [93](#)
- Fortran/C Models, [42](#), [330](#), [335](#), [353](#), [455](#)
 - Abscissa, [463](#)
 - Body, [463](#)
 - Abscissa, [457](#)
 - Declarations, [462](#)
 - Derived Parameters, [457](#), [459](#), [463](#)
 - Edit/Create New Model, [42](#), [455](#)
 - I/O, [464](#)
 - Marginalization, [464](#)
 - $G_j(\Omega, t_i)$, [464](#)
 - Amplitude Range, [465](#)
 - Example, [465](#), [466](#)
 - Model Vectors, [465](#)
 - Ordering Amplitudes, [465](#)
 - Parameter File, [465](#), [467](#)
 - Parameter Order, [465](#)
 - Parameters, [465](#)
- Model Files, [455](#)

- Model Selection, 464
- No Marginalization, 457
 - $S(t_i)$, 455
 - Example, 456
- Parameter File, 458, 459, 465
- Parameters, 463
- Signal, 463
- Subroutine Interface, 460
 - Abscissa, 462
 - Current Set, 460
 - Derived Parameters, 461
 - Maximum No Of Data Values, 461
 - Number Of Abscissa Columns, 461
 - Number Of Data Columns, 461
 - Number Of Derived Parameters, 461
 - Number Of Model Vectors, 461
 - Number Of Parameters, 460
 - Parameters, 461
 - Signal, 462
 - Total Complex Data Values, 461
- Subroutines and Functions, 464
- Frequency Estimation, 114, 132
- Given Exponential Package, 137
 - Bayesian Calculations, 140
 - Files
 - Ascii, 137
 - Bayes Analyze, 137
 - Peak Pick, 137
 - Model Equation, 139
 - Number of data sets, 139
 - Prior Probabilities, 139–141
 - Reports
 - Bayes Accepted, 137, 141
 - Condensed, 141
 - Console log, 141
 - McMC Values, 141
 - Prob Model, 141
 - Symmetries, 141, 148
 - Using, 137
 - Viewers
 - File, 141
 - Plot Results, 141
 - Prior Probabilities, 137, 139
 - Text, 141
 - Widgets
- Constant, 137, 139
- Find Outliers, 137
- Given Order, 27
- Include Constant, 27
- Order, 137, 139
- Given Polynomial Order Package, 285
 - Bayesian Calculations, 288
 - Files
 - Ascii, 285
 - Bayes Analyze, 285
 - Peak Pick, 285
 - Gram-Schmidt, 287
 - Model Equation, 287
 - Number of data sets, 285
 - Prior Probabilities, 289
 - Reports
 - Bayes Accepted, 285, 291
 - Condensed, 291
 - Console log, 291
 - McMC Values, 291
 - Prob Model, 291
 - Scatter Plots, 292
 - Using, 285
 - Viewers
 - File, 290
 - Plot Results, 291
 - Text, 290
 - Widgets
 - Set Order, 285
- Histograms
 - Binned, 381
 - Kernel Density, 381
- Image Model Selection Package, 415
 - Abscissa, 415
 - Fortran/C Models, 415, 417
 - Reports
 - Bayes Accepted, 417
 - Using, 417
 - Viewers
 - Fortran/C Models, 415
 - Image, 415
 - Widgets
 - Noise SD, 415
 - System, 415

- Use Gaussian, 415
- User, 415
- Image Viewer, 59
- Images
 - Flip
 - Horizontal, 63
 - Vertical, 63
 - Grayscale, 63
 - ImageJ, 63
 - Original, 63
- Inversion Recovery Package, 151
 - Bayesian Calculations, 153
 - Model Equation, 153
 - Number of data sets, 153
 - Prior Probabilities, 153
 - Reports
 - Bayes Accepted, 151, 154
 - Condensed, 154
 - Console Log, 154
 - McMC Values, 154
 - Prob Model, 154
 - Using, 151
 - Viewers
 - Plot Results, 154
 - Prior Probability, 151
 - Widgets
 - Find Outliers, 151
- Kernel Density Function Package, 361
 - Ascii File Format, 361
 - Bayesian Calculations, 369
 - Data Requirements, 361
 - Data, Model And Residuals, 369
 - Kernels, 369
 - Biweight, 362
 - Cosine, 362
 - Epanechnikov, 362
 - Exponential, 362
 - Gaussian, 362, 370
 - nonnegative, 361
 - Real Valued, 361
 - Triangular, 362
 - Tricube, 362
 - Triweight, 362
 - Uniform, 362
 - Likelihood, 371
 - Number of data sets, 364
 - Plots
 - Expected Density Function, 367, 368
 - Mean Density Function, 367, 368
 - Posterior Probability for the Kernel Type, 365
 - Posterior Probability for the Number Of Kernels, 366
 - Scatter Plots of Model Averaged Density Function, 368
 - Standard Deviation of the Mean Density Function, 367, 368
 - Prior Probabilities
 - Kernel Center, 371
 - Kernel Smoothing Parameter, 371
 - Kernel Type, 370
 - Number Of Kernels, 370
 - Reports
 - Bayes Accepted, 364
 - Condensed, 372
 - McMC Values, 372
 - Prob Model, 372
 - Using, 364
 - Viewers
 - Ascii, 361
 - Widgets
 - Kernel Type, 364
 - Output Size, 364
- Levenberg-Marquardt, 171
- Linear Phasing Package, 395, 409
 - Interface, 397
 - Model Equation, 398
 - Widgets
 - cf, 403
 - Display, 403
 - Display Array Element, 403
 - fn, 403
 - fn1, 403
 - Image Type, 402
 - Load An Image, 402
 - np, 403
 - nv, 403
 - Process, 403
 - Load Working Directory, 33
 - Logical Independence, 117

- Magnetization Transfer Kinetics Package, **275**
 - Arrhenius Plot, **281**
 - Bayesian Calculation, **278**
 - Boltzmann's Constant, **277**
 - Eyring Equation, **275, 276, 277, 280**
 - Model Equation, **277**
 - Plank's Constant, **277**
 - Prior Probabilities, **279**
 - Reports
 - Bayes Accepted, **277, 281**
 - Condensed, **281**
 - Console log, **281**
 - McMC Values, **281**
 - Prob Model, **281**
 - Sum and Difference Variables, **280**
 - Transmission coefficient, **277**
 - Universal Gas Constant, **277**
 - Using, **277**
 - van't Hoff Plot, **281**
 - Viewers
 - Ascii File, **275**
 - File, **281**
 - Prior Probabilities, **275**
 - Text, **281**
 - Widgets
 - Load, **275, 281**
 - Set, **275**
 - Uncertainty, **275**
- Magnetization Transfer Package, **265**
 - Bayesian Calculations, **267**
 - Files
 - Ascii, **265**
 - Bayes Analyze, **265**
 - Inversion Recovery, **272**
 - Peak Pick, **265**
 - Model Equation, **267**
 - Number of data sets, **265**
 - Prior Probabilities, **265, 270**
 - Reports
 - Bayes Accepted, **267, 272**
 - Condensed, **272**
 - Console log, **272**
 - McMC Values, **272**
 - Prob Model, **272**
 - Three Column Data, **265**
 - Using, **267**
- Viewers
 - Ascii Data, **265**
 - Fid Data, **272**
 - File, **271**
 - Plot Results, **262, 272, 281**
 - Prior Probabilities, **265**
 - Text, **271**
- Widgets
 - Find Outliers, **265**
- Marginalization, **100**
 - Bayes Analyze Package, **174**
 - Behrens-Fisher, **315**
 - Big Magnetization Transfer, **261**
 - Big Peak/Little Peak, **211**
 - Diffusion Tensors, **252**
 - Enter Ascii Model Package, **331**
 - Errors In Variables, **306**
 - Fortran/C Models, **464**
 - Given Exponential, **139**
 - Inversion Recovery, **153**
 - Linear Phasing, **399**
 - Magnetization Transfer, **269**
 - Magnetization Transfer Kinetics, **278**
 - Metabolic Analysis, **225**
 - Nonexhaustive Hypotheses, **101**
 - Nuisance Hypotheses, **100**
 - Nuisance Parameter, **100**
 - Unknown Number of Exponentials, **146**
- Markov chain Monte Carlo, **132, 439**
 - Acceptance Rate, **444**
 - Annealing Schedule, **91, 442**
 - Dynamic, **443**
 - Linear, **442**
 - Killing Simulations, **443**
 - Maximum Posterior Probability, **91**
 - Metropolis-Hastings, **439**
 - Mixing, **91**
 - Monte Carlo Integration, **440**
 - Multiple Simulations, **441**
 - Posterior Probability, **440**
 - Random Number Generators, **440**
 - Repeats, **91**
 - Sampling, **91**
 - Simulated Annealing, **442**
 - the Proposal, **444**

- MaxEnt Density Function Estimation Package, **373**
 - Data Requirements, **381**
 - Plots
 - Contour/Scatter, **375, 379**
 - Number Of Multipliers, **375, 378**
 - Reports
 - Bayes Accepted, **375**
 - Console Log, **375**
 - Using, **375**
 - Viewers
 - Ascii, **373**
 - Plot, **375, 378**
 - Prior Probabilities, **373**
 - Widgets
 - Histogram Size, **373**
 - Order, **373**
- Maximum Entropy Method Of Moments, **102, 377, 381**
 - Advantages, **386**
 - Problems, **386**
 - Review, **381**
- Maximum Entropy Method Of Moments Package
 - Bayesian Calculations, **387**
 - Plots
 - Data, Model and Residuals, **380**
- Menus
 - Files, **24, 35**
 - 4dfp, **37, 38**
 - Abscissa, **35, 39**
 - ASCII, **35, 36**
 - Binary, **38**
 - Bruker, **37**
 - Bruker 2dseq, **38**
 - Bruker Stack, **38**
 - DICOM, **37, 38**
 - FDF, **37, 38**
 - fid, **36, 37**
 - General Binary, **37**
 - Images, **35**
 - Import Working Directories in Batch, **40**
 - Import Working Directory, **40**
 - Load Images, **36, 37, 59**
 - Load Working Directory, **35**
 - Multi-Column Text, **37, 38**
 - Save Working Directory, **35, 39**
 - Siemens IMA, **37, 38**
 - Single-Column Text, **38**
 - Spectroscopic Fid, **35**
 - Test Data, **35, 39**
 - Text k-space, **36**
 - Text k-space fid, **37**
 - User Manual, **35, 39**
- Help, **24**
- Packages, **22, 24, 33, 40**
- Settings, **46**
 - Add Server, **48**
 - Auto Configure Server, **48**
 - MCMC Parameters, **24, 46, 48**
 - Min Annealing Steps, **48, 48**
 - Port number, **48**
 - Preferences, **49, 63**
 - Remove Server, **48, 49**
 - Repetitions, **46, 48**
 - Server Name, **48**
 - Server Setup, **24, 26, 48**
 - Set Window Size, **49**
 - Simulations, **46, 48**
 - View Server Installation Info, **48, 49**
- Spectroscopy fid, **36**
- Utilities, **24, 50**
 - Memory Monitor, **50**
 - Software Updates, **50**
 - System Information, **50**
- WorkDir
 - Creating, **22, 33, 46**
 - Deleting, **22, 33, 46**
 - List, **24, 46**
 - Loading, **46**
 - Name, **46**
 - Popup, **47**
- Model Comparison
 - Big Peak/Little Peak Package, **211**
- model orthonormal definition, **349**
- Mouse
 - Control-left, **59**
- Fid Data Viewer
 - Left, **56**
 - Right, **56**
 - Shift-left, **59**
- Multiplets
 - J-Coupling

- Center, [159](#)
- Primary, [159](#)
- Secondary, [159](#)
- Newton-Raphson, [171](#)
- Noise Standard Deviation, [64](#)
- Non-Linear Phasing Package, [405](#)
 - Calculations, [407](#)
 - Model Equation, [405](#), [407](#)
 - Widgets
 - Process, [409](#)
 - Write Ascii images, [409](#)
 - Write imaginary images, [409](#)
- Nuisance Parameter, [100](#), [115](#), [135](#)
- Nyquist Critical Frequency, [111](#), [127](#)
- orthonormal, [349](#)
- Outliers, [475](#)
 - Mean Parameter, [477](#)
 - Model, [475](#)
 - Prob Number of, [476](#)
 - Proposal, [475](#)
 - Red dot, [477](#)
 - Weighted Average, [477](#)
- Packages
 - Analyze Image Pixel Unique, [423](#)
 - Bayes Analyze, [20](#), [43](#), [57](#), [155](#), [200](#)
 - Bayes Find Resonances, [21](#), [239](#)
 - Bayes Test Data, [427](#)
 - Behrens-Fisher, [21](#), [44](#), [311](#)
 - Big Magnetization Transfer, [20](#), [43](#), [259](#)
 - Big Peak/Little Peak, [20](#), [43](#), [207](#)
 - Binned Density Function Estimation, [355](#)
 - Binned Histograms, [21](#), [44](#)
 - Diffusion Tensors, [20](#), [40](#), [247](#)
 - Enter ASCII Model, [42](#)
 - Enter Ascii Model, [20](#), [329](#)
 - Enter ASCII Model Selection, [42](#)
 - Enter Ascii Model Selection, [20](#), [341](#)
 - Errors In Variables, [21](#), [44](#), [303](#)
 - Find Resonances, [43](#)
 - Given Exponential, [20](#), [40](#), [137](#)
 - Given Polynomial Order, [285](#)
 - Image Model Selection, [415](#)
 - Image Pixel, [21](#), [45](#), [411](#)
 - Image Pixel Model Selection, [22](#), [45](#)
 - Inversion Recovery, [20](#), [40](#), [151](#)
 - Kernel Density Function, [361](#)
 - Linear Phasing, [21](#), [44](#), [395](#)
 - Magnetization Transfer, [20](#), [42](#), [265](#)
 - Magnetization Transfer Kinetics, [20](#), [43](#), [275](#)
 - Maximum Entropy Method Of Moments, [21](#), [44](#), [373](#)
 - Metabolic Analysis, [21](#), [43](#), [219](#)
 - Non-Linear Image Phasing, [21](#), [45](#), [405](#)
 - Polynomials
 - of Given Order, [21](#), [44](#)
 - of Unknown Order, [21](#), [44](#)
 - Test ASCII Model, [42](#)
 - Test Ascii Model, [20](#), [337](#)
 - Unknown Number of Exponentials, [20](#), [40](#), [143](#)
 - Unknown Polynomial Order, [293](#)
- Parameter File, [42](#)
- Number Of
 - Abscissa, [458](#)
 - Data Columns, [458](#)
 - Model Vectors, [458](#)
 - Priors, [458](#)
- Prior Probability, [459](#)
 - Amplitude, [460](#)
 - High, [459](#)
 - Low, [459](#)
 - Mean, [459](#)
 - NonLinear, [460](#)
 - Ordered, [460](#)
 - Parameter File, [459](#)
 - Peak, [459](#)
 - Prior Type, [460](#)
 - Standard Deviation, [459](#)
- Phase Cycling, [162](#)
- Plot Results Viewer, [71](#)
- Plots
 - Data and Model, [81](#)
 - Data, Model and Residuals, [81](#)
 - Expected Log Likelihood, [88](#)
 - Logarithm of the Posterior Probability, [91](#)
 - Maximum Entropy Histogram, [84](#)
 - Maximum Entropy Histograms, [83](#)
 - McMC Samples, [83](#), [85](#)
 - Parameter Vs Posterior Probability, [86](#), [87](#)

- Posterior Probability, [82](#)
- Posterior Probability Vs Parameter Value, [86](#)
- Residuals, [81](#)
- Scatter, [88](#), [91](#)
- png graphics, [59](#)
- Posterior Probability Vs Parameter Value, [86](#)
- Power Spectrum, [112](#), [123](#), [124](#)
- Prior Probabilities
 - Bayes Phase, [399](#)
 - Big Magnetization Transfer, [261](#)
 - Big Peak/Little Peak, [212](#)
 - Diffusion Tensor, [253](#)
 - Enter Ascii Model, [331](#), [333](#)
 - Errors In Variables, [306](#)
 - Magnetization Transfer, [269](#)
 - Magnetization Transfer Kinetics, [279](#)
 - Non-Linear Phasing Package
 - A, [408](#)
 - θ , [408](#)
- Prior Probability, [42](#), [65](#), [65](#)
 - Exponential, [67](#), [459](#)
 - Gaussian, [67](#), [104](#), [106](#), [459](#)
 - Jeffreys', [118](#)
 - Normalization Constant, [67](#)
 - Parameter, [68](#), [459](#)
 - Positive, [68](#), [460](#)
 - Uniform, [67](#), [103](#), [118](#), [459](#)
- Prior Viewer, [65](#), [93](#)
- Probabilities
 - Expected Log Likelihood, [453](#)
 - Likelihood, [453](#)
 - Posterior, [453](#)
 - Prior, [453](#)
- Product Rule, [99](#), [119](#), [344](#), [439](#)
- Referencing
 - Setting, [59](#)
- Reports
 - Accepted File, [76](#)
 - McMC Values File
 - General Description, [449](#)
 - Maximum Posterior Probability Simulations, [451](#)
 - Mean Values, [452](#)
 - Prior, [450](#)
 - Standard Deviations, [453](#)
- Restoring An Analysis, [22](#), [35](#), [40](#)
- ROI
 - Expanding, [63](#)
 - Pixels, [63](#)
 - Point, [62](#)
 - Polygon, [62](#)
 - Square, [62](#)
- Saving An Analysis, [35](#), [39](#)
- Schuster Periodogram, [112](#), [123](#)
- Screen Captures, [49](#)
- Settings
 - httpd server, [19](#)
- Software
 - Bayes Account, [29](#)
 - CC, [29](#)
 - Fortran, [29](#)
 - Installation, [29](#)
 - javaws, [29](#)
 - OS requirements, [29](#)
 - root requirements, [30](#)
- Start Up Window, [22](#), [33](#)
- Steepest Descents, [173](#)
- Subdirectories, [469](#)
 - Bayes, [39](#)
 - Bayes.model.fid, [470](#)
 - Bayes.Predefined.Spec, [469](#)
 - Bayes.test.data, [39](#)
 - BayesAnalyzeFiles, [470](#)
 - BayesAsciiModels, [93](#), [469](#)
 - BayesOtherAnalysis, [35](#), [73](#), [470](#)
 - fid, [36](#), [53](#)
 - images, [36](#), [38](#), [39](#), [59](#), [470](#)
 - model.compile, [470](#)
 - plugins, [470](#)
 - Properties, [470](#)
 - Resources, [470](#)
 - Spectroscopic
 - fid, [470](#)
 - Working Directories, [470](#)
- Subroutine Names, [464](#)
- Sufficient Statistics, [122](#)
 - Definition, [105](#)
 - Location Parameter, [108](#)
- Sum Rule, [100](#), [119](#), [344](#), [440](#)

- Test Ascii Model Package, **337**
 - Reports
 - Bayes Accepted, **339**
 - Mcmc Values, **339**
 - Using, **339, 428**
 - Viewers
 - Ascii Data, **337**
 - Fortran/C Models, **337**
 - Prior Probabilities, **337**
 - Widgets
 - Build, **337**
 - Find Outliers, **339**
 - System, **337**
 - User, **337**
- Thermodynamic Integration, **445, 449**
- Uninstall, **49**
- Unknown Number of Exponentials Package, **143**
 - Bayesian Calculations, **145**
 - Model Equation, **145**
 - Reports
 - Bayes Accepted, **143, 148**
 - Condensed, **148**
 - Console Log, **148, 149**
 - McMC Values, **148**
 - Prob Model, **148**
 - Using, **143**
 - Viewers
 - File, **148**
 - Plot Results, **149, 150**
 - Prior, **143**
 - Text, **148**
 - Widgets
 - Constant, **143**
 - Find Outliers, **143**
 - Order, **143**
- Unknown Polynomial Order Package, **293**
 - Bayesian Calculations, **295**
 - Files
 - Ascii, **293**
 - Bayes Analyze, **293**
 - Peak Pick, **293**
 - Model Equation, **295**
 - Number of data sets, **293**
 - Reports
 - Bayes Accepted, **293, 299**
 - Condensed, **299**
 - Console Log, **298, 299**
 - McMC Values, **299**
 - Polynomial Order Plot , **301**
 - Prob Model, **299**
 - Using, **293**
 - Viewers
 - File, **299**
 - Text, **299**
 - Widgets
 - Set Order, **293, 294**
 - Unknown Order, **293, 294**
- Viewers, **27, 52**
 - ASCII Data, **36**
 - Ascii Data, **27, 53, 56, 63, 137, 265, 275, 285, 293, 311, 329, 337, 341**
 - Expanding Plot, **53**
 - Printing, **53**
 - Right click, **53**
 - Bayes Model, **160**
 - Fid Data, **27, 265**
 - fid Data, **53, 53, 285, 293**
 - Auto Range, **59**
 - Autoscale, **56**
 - Clear Cursors, **56**
 - Clear Data, **57**
 - Copy, **59**
 - Cursor, **56**
 - Data Info, **57**
 - Expand, **56**
 - fn, **57**
 - Full, **56**
 - Get Peak, **56**
 - Phase Popup, **57**
 - Print, **59**
 - Properties, **59**
 - Referencing, **59**
 - Save As, **57, 59**
 - Set Preference, **57**
 - Units, **59**
 - Zoom, **59**
 - Fid Model, **27**
 - fid Model, **68, 186**
 - Build BA Model, **70, 159**
 - Data, **71**

- Horizontal, 71
- Model, 71
- Overlay, 71
- Report, 71
- Residual, 71
- Stacked, 71
- Trace, 71
- Vertical, 71
- File, 28, 80
- Fortran/C Models, 93, 330
- Image, 27, 59, 415
 - Autoset Grayscale, 61
 - Copy Selected, 62
 - Delete All, 61
 - Delete Selected, 61
 - Display Full, 61
 - Element Selection, 60
 - Export, 62
 - Get Statistics, 64, 65
 - Get Threshold Statistics, 65
 - Grayscale, 63
 - Image Selection, 60
 - List, 59
 - Load Selected Pixels, 61
 - Max, 64
 - Mean, 64
 - Min, 64
 - Right Click, 61
 - RMS, 64
 - Save Displayed, 62
 - Save Statistics, 65
 - Sdev, 64
 - Set Image Area, 62
 - Show Histogram, 61
 - Show Info, 62
 - Slice, 62
 - Slice Selection, 60
 - Statistics, 60
 - Value, 64
 - View Selected Pixels, 61
 - Viewer Settings, 62
 - Viewing, 62
 - X Pos, 64
 - Y Pos, 64
- Plot Results, 28, 71
- Prior, 27, 65
 - Prior Probabilities, 138, 312
 - Text, 141, 271, 281, 290, 309, 322, 335, 353
 - Text Results, 26, 28, 52, 74
 - Bayes Analyze, 176
- Widgets
 - Analyze Image Pixel Package
 - Build, 411
 - Find Outliers, 411
 - Get Statistics, 413
 - System, 411
 - User, 411
 - Analyze Image Pixel Unique Package
 - Build, 423
 - Find Outliers, 423
 - Get Statistics, 425
 - System, 423
 - User, 423
 - Ascii Data Viewer
 - Delete, 53
 - Left-mouse, 53
 - Right-mouse, 53
 - Bayes Analyze Package
 - By, 158, 176
 - First Point, 163
 - From, 158, 176
 - Imag Offset, 163
 - Mark, 159
 - Max New Res, 157
 - New, 159
 - Noise, 158
 - Phase, 157
 - Primary, 158
 - Real Offset, 163
 - Remove, 159
 - Remove All, 159
 - Reset, 159, 193
 - Restore, 159
 - Save, 159
 - Secondary, 159
 - Shim Order, 157, 163
 - Signal, 158
 - To, 158, 176
 - Bayes Find Resonances Package
 - Build FID Model, 240, 241, 246
 - Constant, 239, 242

- First Trace, 239
- Last Trace, 239
- Model Fid Number, 241
- Phase Model, 239, 242
- Bayes Metabolite Package
 - Fid Model, 221
 - Fid Model Viewer, 221
 - Load System Metabolite File, 219
 - Load System Resonance File, 221
 - Load User Metabolite File, 219
 - Load User Resonance File, 221
 - Shift Left, 221, 222
 - Shift Right, 221, 222
- Bayes Test Data Package
 - # Images, 427
 - # Slices, 427
 - Abscissa, 427
 - ArrayDim, 427
 - Build, 427
 - Get Job, 428
 - Max Value, 427
 - Noise SD, 427
 - Pe, 427
 - Ro, 427
 - Run, 428
 - Set (server), 428
 - Status, 428
 - System, 427
 - User, 427
- Big Magnetization Transfer Package
 - Find Outliers, 259
- Big Peak/Little Peak Package
 - Metabolite, 207
 - Solvent, 207
- Diffusion Tensor Package
 - Abscissa Options, 248
 - Find Outliers, 247
 - Include Constant, 247, 248, 255
 - Tensor Number, 247, 248, 255
 - Use b Matrix, 255
 - Use b Vectors, 254, 255
 - Use g Vectors, 254
- Enter Ascii Model Package
 - Find Outliers, 329
 - System, 329
 - User, 329
- Enter Ascii Model Selection Package
 - Find Outliers, 341
 - System, 341
 - User, 341
- Errors In Variables Package
 - Given Errors In, 303
 - Order, 303
- Fid Data Viewer
 - Autoscale, 56
 - Clear Cursors, 56
 - Cursor A, 56
 - Cursor B, 56
 - Delta, 56
 - Display Type, 56
 - Expand, 56
 - Full, 56
 - Get Peak, 56
 - Left-mouse, 56
 - Options, 57, 59
 - Right-mouse, 56
 - Trace, 70
- Fortran/C Model Viewer
 - Abscissa Spinner, 93
 - Add Prior, 96
 - Allow/Disallow Editing, 97
 - Cancel and Exit, 96
 - Changing Models, 94
 - Code, 93, 94
 - Compile Results, 97
 - Compiling, 96
 - Create/Edit Model, 93
 - Data Columns Spinner, 93
 - Derived, 96
 - Edit/Create New Model, 93, 94
 - High, 97
 - Low, 97
 - Mean, 97
 - Model, 96
 - Model Vectors, 93
 - Name (parameter), 97
 - Order, 97
 - Parameter Type, 97
 - Parameters button, 93, 94, 96
 - Prior Type, 97
 - Priors, 96
 - Remove All (priors), 96

- Remove Prior, 96
- Remove Selected Model, 93
- Save and Load, 96
- Standard Deviation, 97
- Given Exponential Package
 - Constant, 137, 139
 - Find Outliers, 137
 - Order, 137, 139
- Given Polynomial Order Package
 - Set Order, 285
- Global
 - Bayes Find Outliers, 27
 - Cancel, 26, 51
 - Edit Servers, 26
 - Get Job, 26, 51, 137, 143, 151, 155, 209, 221, 241, 247, 259, 267, 277, 285, 293, 305, 311, 331, 339, 343, 357, 364, 375, 413, 417, 425, 428
 - Reset, 27
 - Restore Analysis, 22
 - Run, 26, 51, 137, 143, 151, 155, 207, 221, 241, 247, 248, 259, 267, 277, 285, 293, 305, 311, 329, 337, 343, 357, 364, 373, 413, 415, 425, 428
 - Save, 27
 - Set (server), 26, 52, 137, 143, 151, 155, 207, 221, 239, 247, 259, 265, 277, 285, 293, 305, 311, 329, 337, 343, 355, 364, 373, 413, 415, 425, 428
 - Status, 26, 52, 137, 143, 151, 155, 207, 221, 241, 247, 259, 267, 277, 285, 293, 305, 311, 329, 337, 343, 355, 364, 373, 413, 415, 425, 428
- Image Model Selection Package
 - System, 415
 - User, 415
- Image Viewer
 - Element Number, 62
 - Get Statistics, 64
 - Get Threshold Statistics, 65
 - Grayscale, 63
 - Save Statistics, 65
 - Slice Number, 62
 - Value, 64
 - X Pos, 64
 - Y Pos, 64
- Inversion Recovery Package
 - Find Outliers, 151
- Kernel Density Function Package
 - Kernel Type, 364
 - Output Size, 364
- Linear Phasing Package
 - cf, 403
 - Display, 403
 - Display Array Element, 403
 - fn, 403
 - fn1, 403
 - Image Type, 402
 - Load An Image, 402
 - np, 403
 - nv, 403
 - Process, 403
- Magnetization Transfer Kinetics Package
 - Load, 275, 281
 - Set, 275
 - Uncertainty, 275
- Magnetization Transfer Package
 - Find Outliers, 265
- MaxEnt Density Function Estimation Package
 - Histogram Size, 373
 - Order, 373
- Non-Linear Phasing Package
 - Process, 409
 - Write Ascii images, 409
 - Write imaginary images, 409
- Prior Viewer
 - High, 65
 - Low, 65
 - Mean, 65
 - Prior Type, 67
- Server
 - Edit, 52
 - Name, 26, 52, 52
 - Set (server), 48
 - Setup, 48, 52
- Test Ascii Model Package
 - Find Outliers, 339
 - System, 337
 - User, 337
- Text Results Viewer
 - Copy, 74

- Down arrow, [74](#)
- Enable Editing, [74](#)
- Print, [74](#)
- Save (a copy), [74](#)
- Save As, [74](#)
- Settings, [74](#)
- Up arrow, [74](#)
- Unknown Number of Exponentials Package
 - Constant, [143](#)
 - Find Outliers, [143](#)
 - Order, [143](#)
- Unknown Polynomial Order Package
 - Set Order, [293](#), [294](#)
 - Unknown Order, [293](#), [294](#)
- WorkDir
 - Creating, [22](#), [33](#), [46](#)
 - Deleting, [22](#), [33](#), [46](#)
 - List, [24](#), [46](#)
 - Loading, [46](#)
 - Name, [46](#)
 - Popup, [47](#)