Bayesian Data-Analysis Toolbox
Release 4.23, Manual Version 3

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September 18, 2018

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 model image, outside the brain the noise oscillates around zero and close inspection of the images will revel 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 my 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 processes 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

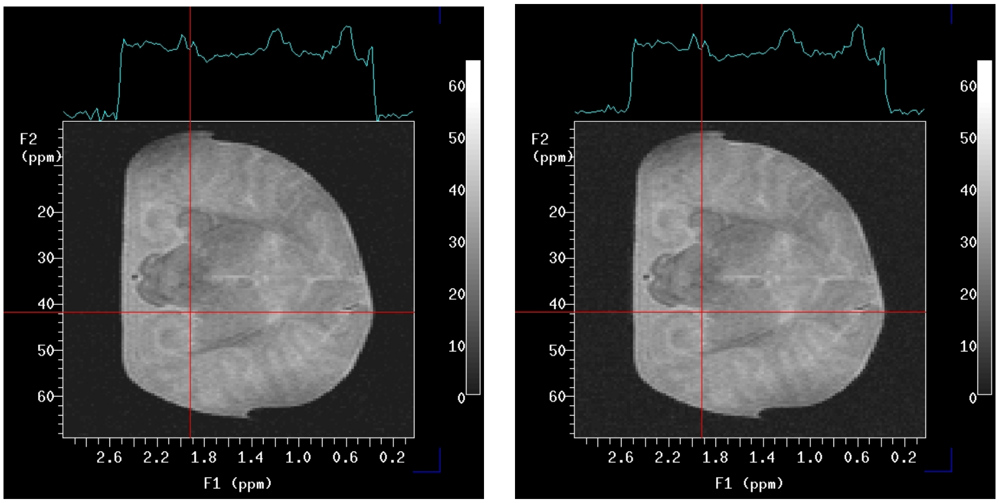


Figure 26.1: The left panel is an example of an absorption mode image while the right panel is the same image in absolute value. A single trace has been displayed on both images. Note that in the absorption image outside the brain the noise oscillates around zero and the image comes down faster on the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

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

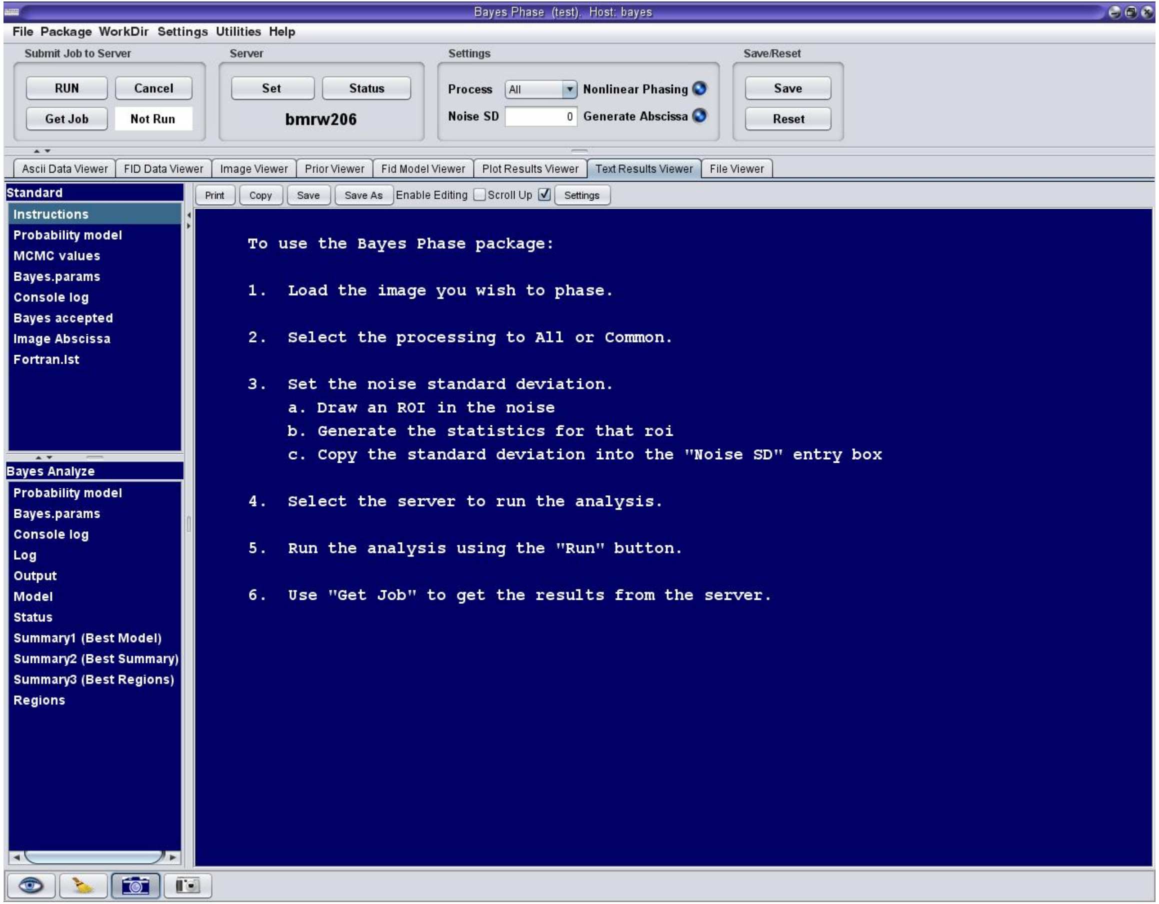
The Bayes Phase package is accessed by selecting the "Phase An Image" button on the dispatching menu. When this button is activated the interface window shown in Fig. 26.2 is displayed. The upper panel in this figure is the heart of the VnmrJ interface while the lower panel is the Vnmr interface. Both 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



```
To use the Bayes Phase package:

1.  Load the image you wish to phase.

2.  Select the processing to All or Common.

3.  Set the noise standard deviation.
    a. Draw an ROI in the noise
    b. Generate the statistics for that roi
    c. Copy the standard deviation into the "Noise SD" entry box

4.  Select the server to run the analysis.

5.  Run the analysis using the "Run" button.

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

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:

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

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

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

where B_{kj} are the amplitudes of the image in the jth k-space acquisition. Similarly, the phase θ_j is the constant phase in the jth 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

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

for the real data, and

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

for the quadrature data where

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

and

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

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

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

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

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

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

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

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

where we have not factored the prior probability for the amplitudes, $P(B_{1j} \ldots B_{N_xj}|I)$, 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

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

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:

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

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

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

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:

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

with

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

where δ_{kl} is a delta function,

$$\overline{d^2_{xj}} \equiv \frac{1}{N_x}\sum_{i=1}^{N_x} d^2_{ij} \tag{26.17}$$

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

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

and

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

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 from 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

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

where

$$T_{ij} \equiv \cos\theta F_{Rij} + \sin\theta F_{Iij} \tag{26.21}$$

and

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

with

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

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_o Bessel function, one obtains

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

with

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

and

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

We note in passing that the quantity

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

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

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

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

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

This probability density function is of the form of Students 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 $\Theta + 180°$. 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 BayesOtherAnalysis 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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